Ion Induction Linacs for Inertial Fusion and High Energy Density Physics

William A. Barletta

Director, United States Particle Accelerator School

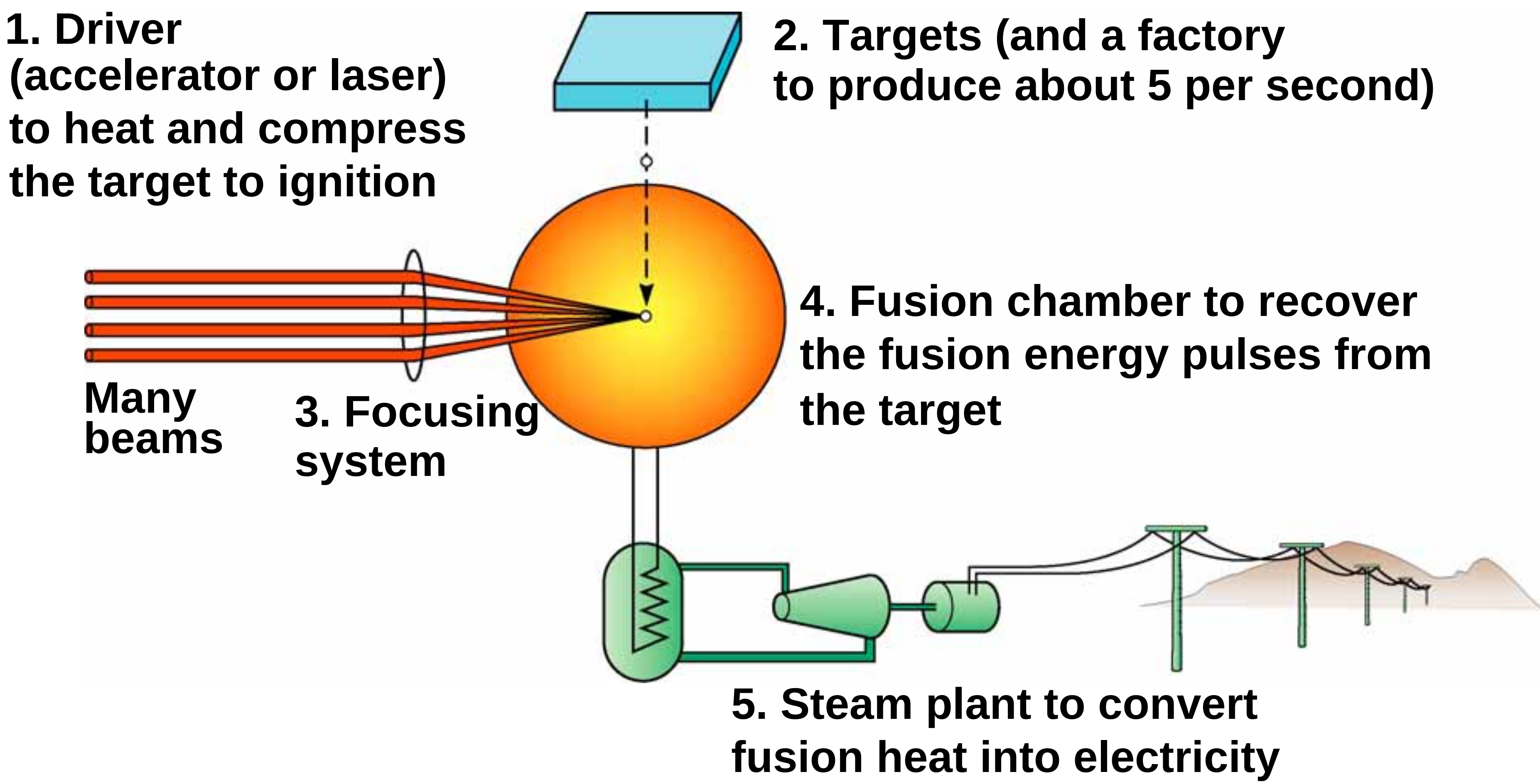
Dept. of Physics, MIT

Motivations

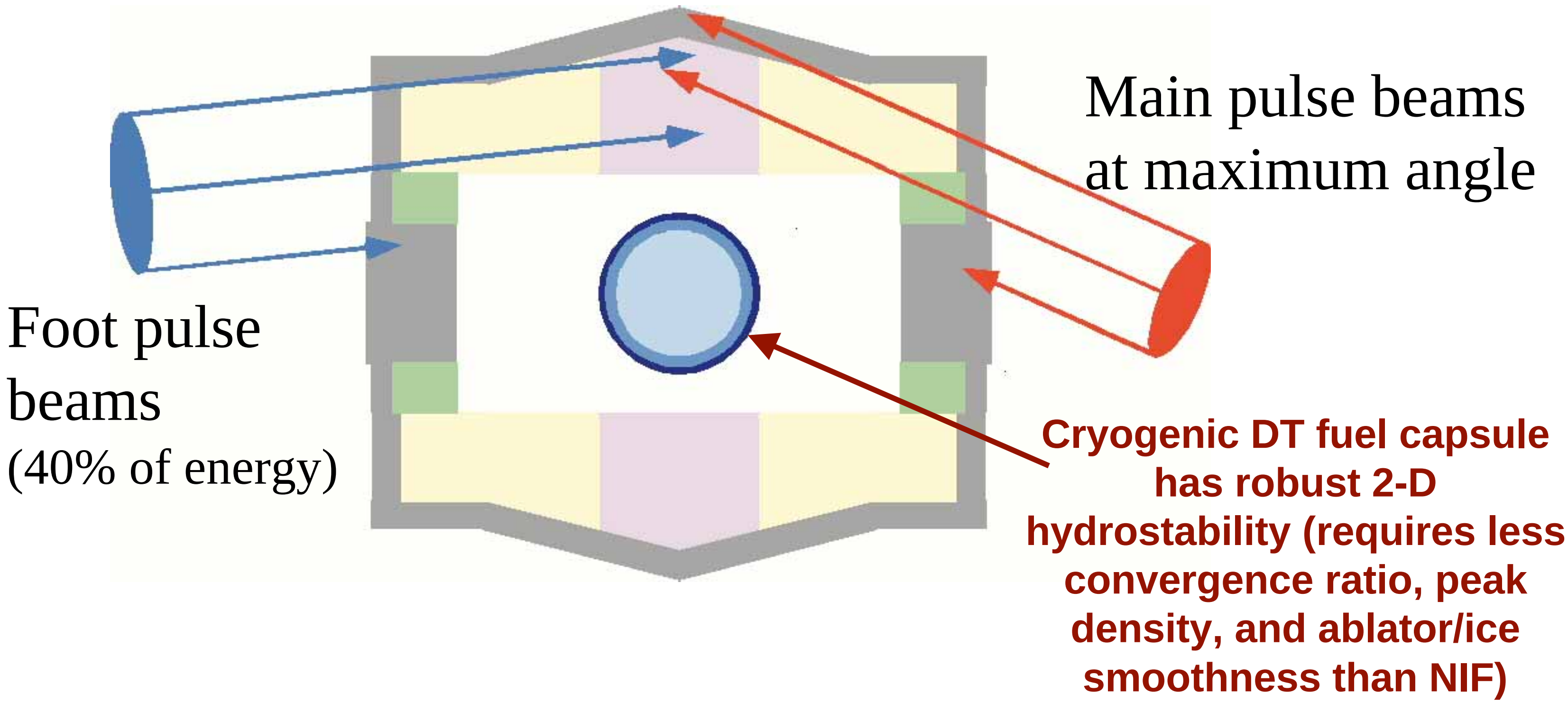
Heavy ion driven inertial fusion

And High Energy Density Physics

An inertial fusion power plant has several parts



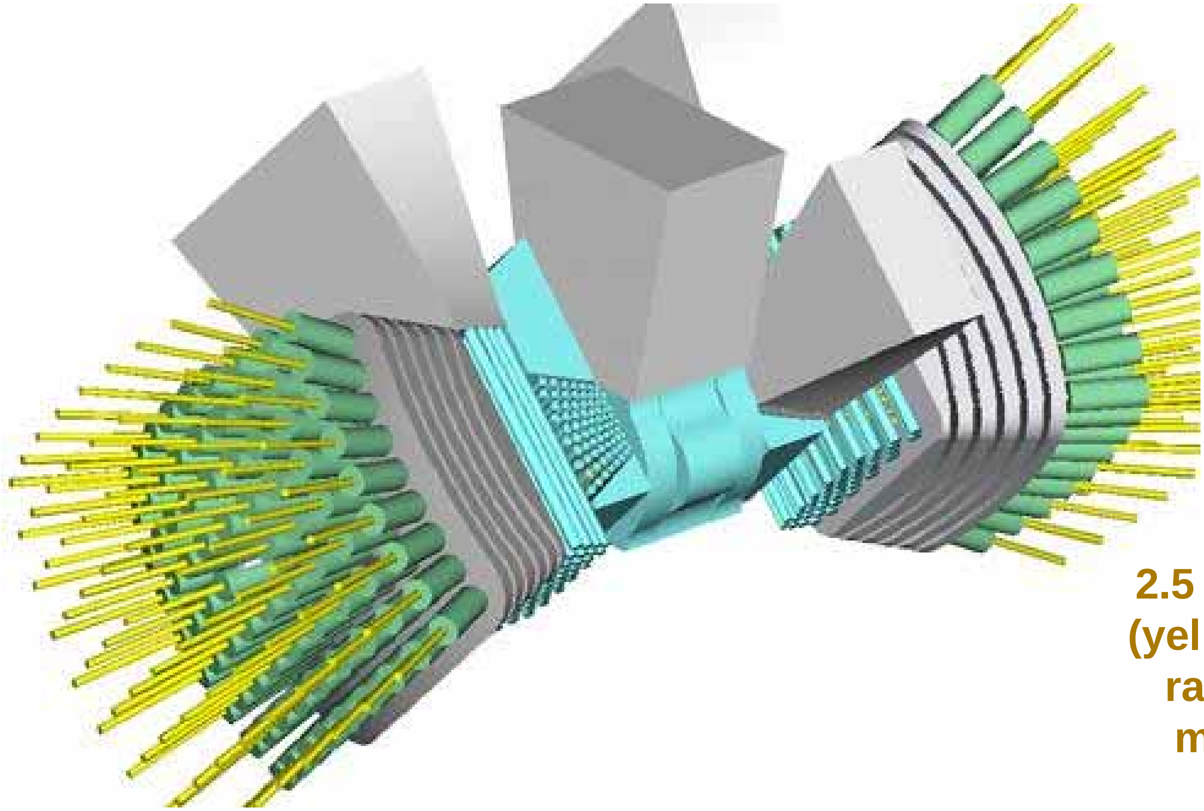
Target design is a variation of the distributed radiator target (DRT)



New design allows beams to come in from larger angle, ~ 24° off axis.

Yield = 400 MJ, Gain = 57 at E_{driver} = 7 MJ

Chamber walls are protected from neutron damage by thick liquid jets



2.5 GeV Xenon beams (yellow) focus to 2 mm radius spots with 6 meter focal length

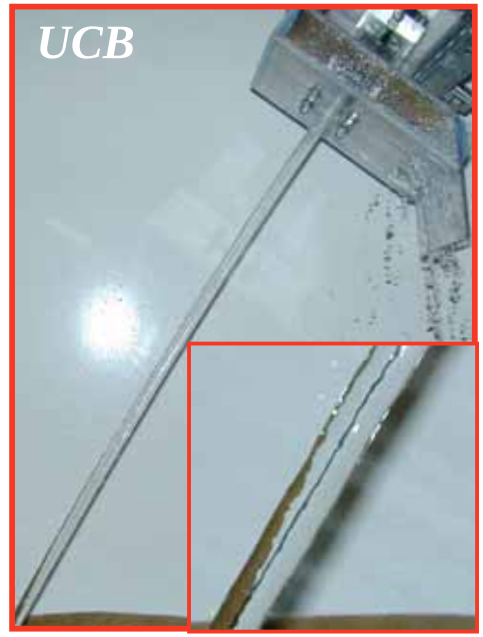
160-beam HYLIFE-II chamber cutaway: Focus magnets (in green)

Molten-salt-FLiBe jets (in light blue)

Chamber is designed for 30 yr lifetime.

Current research on thick-liquid protected chambers

UCB facility studies
Flow conditions approach correct Reynolds and Weber numbers for HYLIFE-II

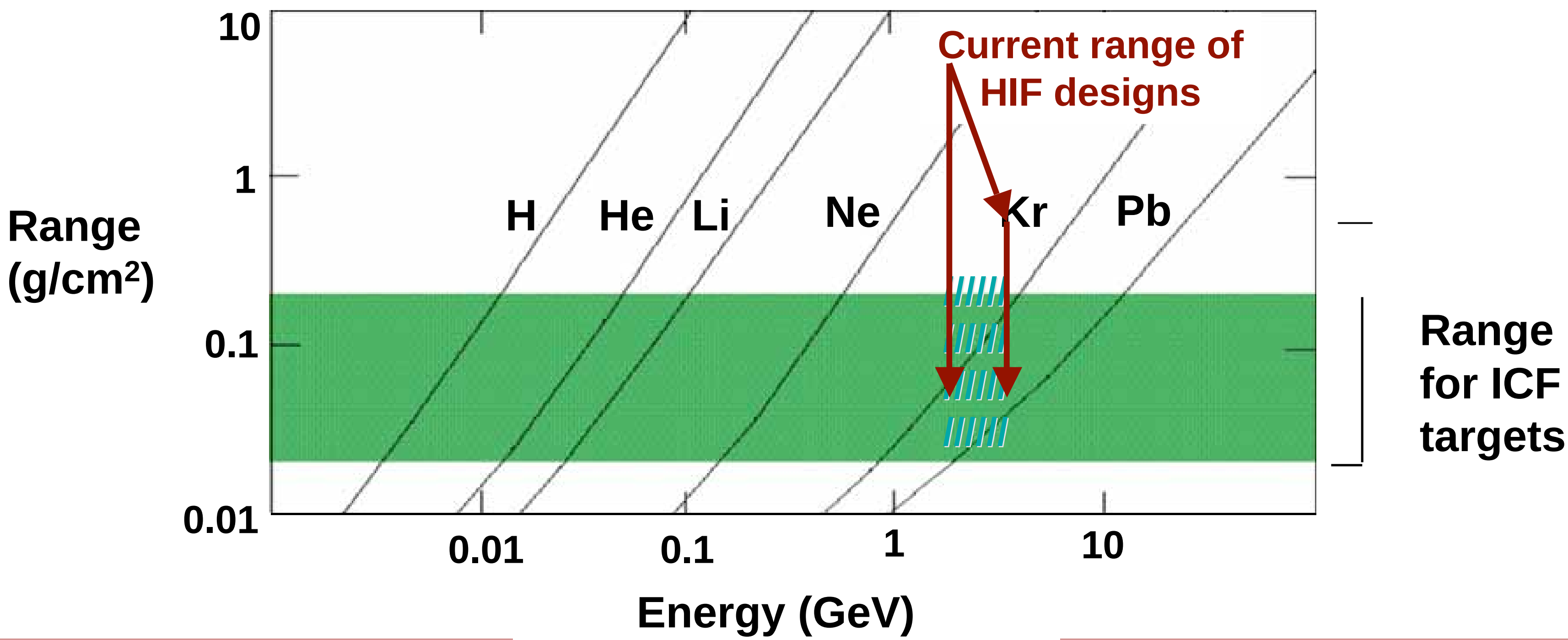


Highly smooth cylindrical jets

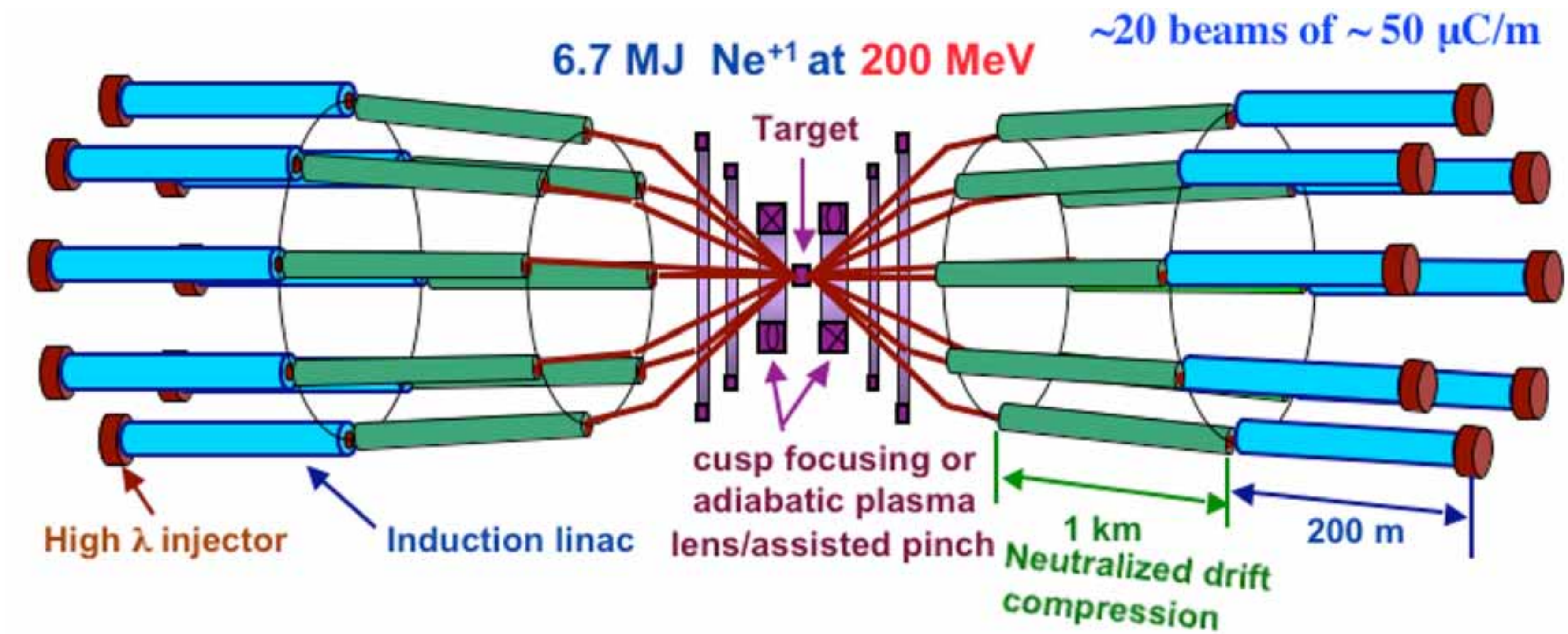
Slab jet arrays with disruptions

Heavier ions ==> higher voltage ==> lower current beams

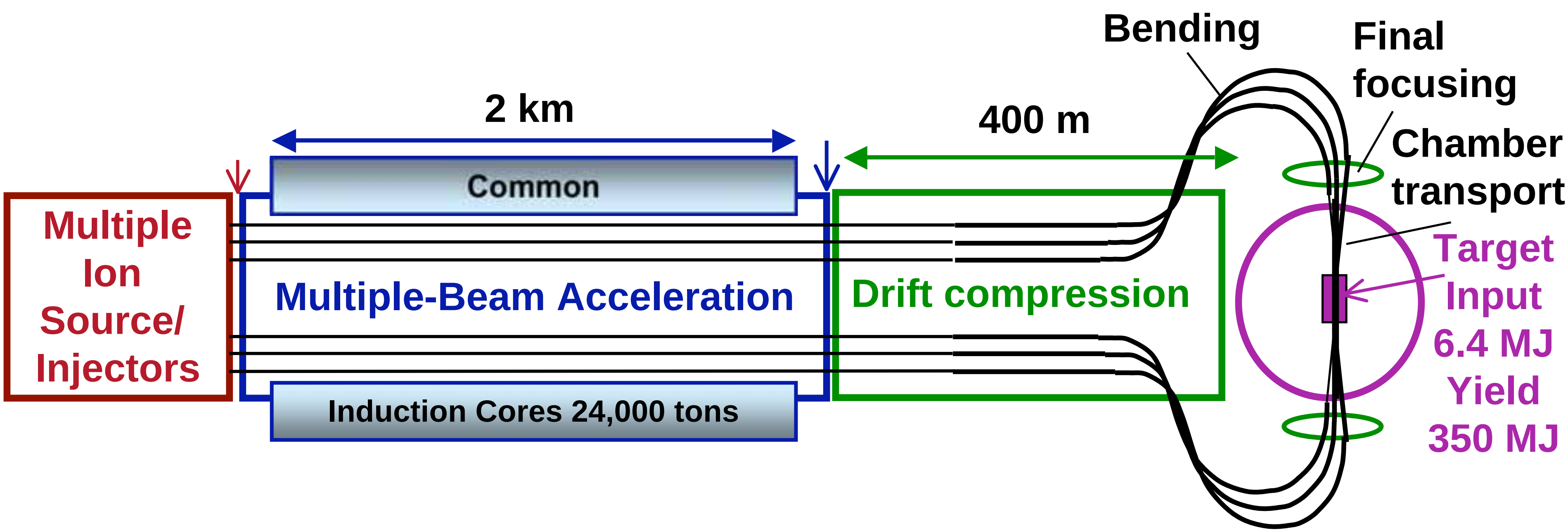
- Collective effects are reduced with heaviest ions
  - More energy/particle ==> fewer particles (~10^{15} total ions).
- Cost tradeoff: lower mass ions ==> lower voltage ==> lower cost
  - Compromise with 2.5 GeV Xenon.
- SC magnets can confine beam against its space charge during acceleration.



An example of a driver with not-so-heavy ions



2.5 GeV 112-beam fusion driver: 6.4 MJ of Xe^{+1}



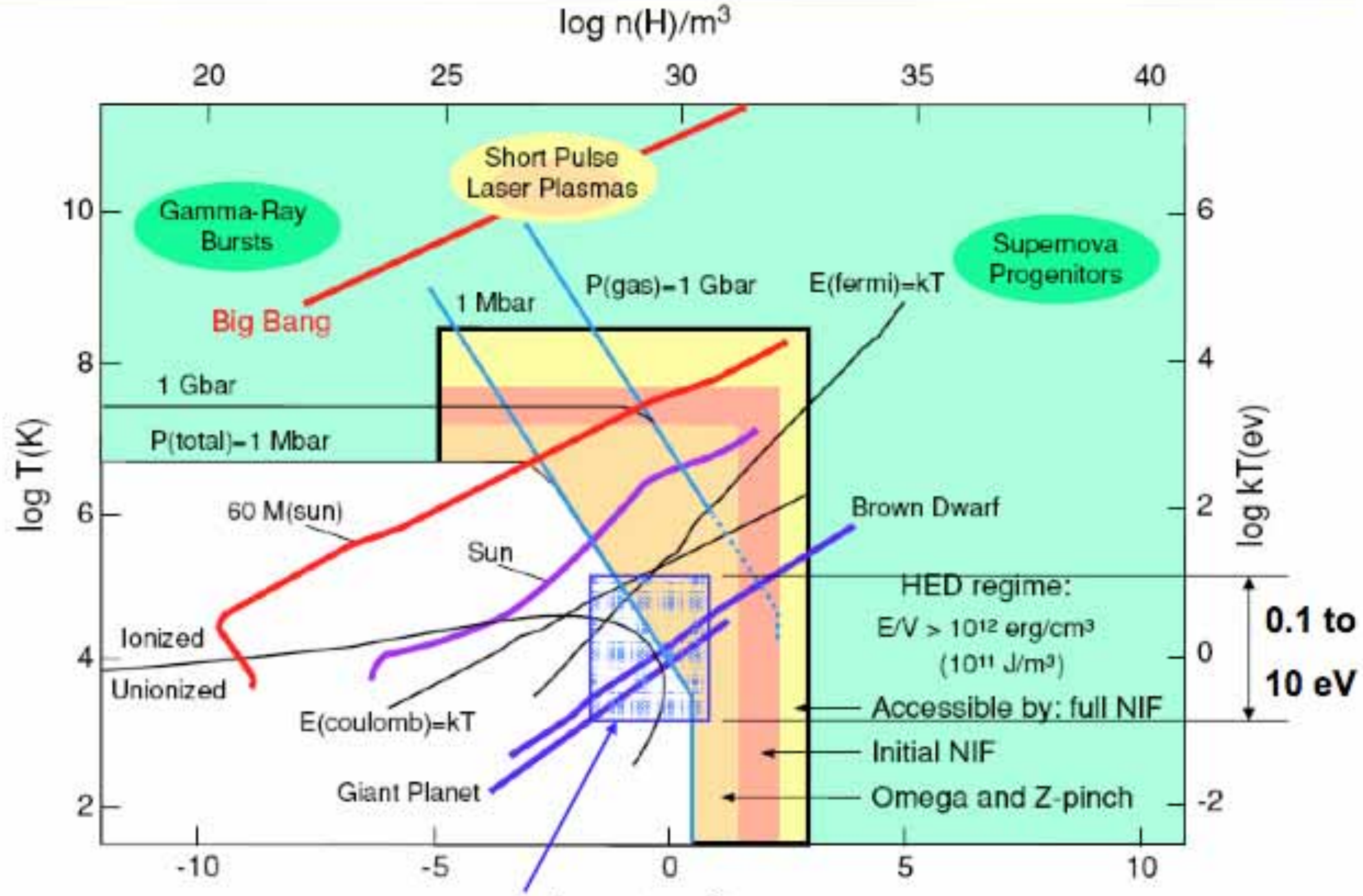
24,000 tonne induction cores

$720M hardware, $1 B direct, $2.1 B total capital cost

Beam requirements for HIF

- Representative set of parameters for indirect-drive targets
  - ➙ 500 Terawatts of beam power
  - ➙ beam pulse length ~ 10 ns
  - ➙ range 0.02 - 0.2 g/cm^2
  - ➙ focus such a large beam to a spot of ~1-5 mm radius
  - ➙ desired focal length ~6 m (maximum chamber size
- Basic requirements ==> certain design choices
  - ➙ parallel acceleration of multiple beams
  - ➙ acceleration of needed charge in a single beam is uneconomical
  - ➙ emittance required to focus single large beam extremely difficult

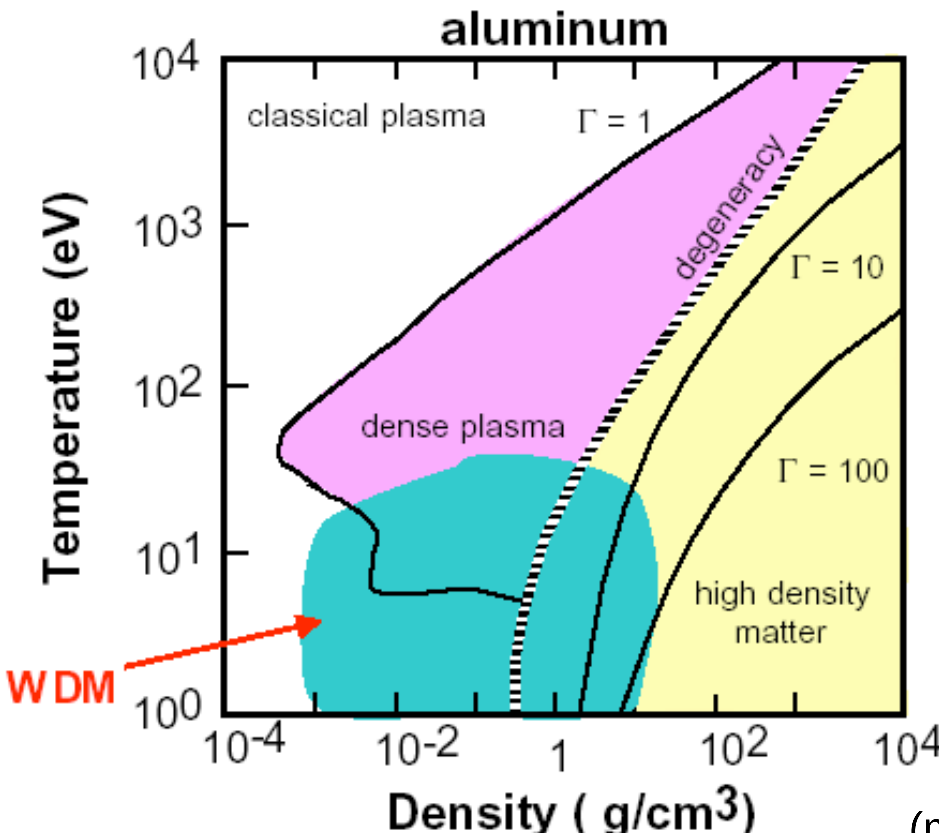
Map of the High Energy Density Physics Universe



Some of the most interesting physics is in this E>kT region accessible to heavy-ion beams

Warm-dense-matter regime of high energy density physics to be potentially driven by ion beams

- WDM is that region in temperature (T) - density (ρ) space that is:
  1) Not described as normal condensed matter.
  2) Not described by weak coupling theory.



- Γ is the strong coupling parameter, the ratio of the interaction energy between the particles, V_{ii}, to the kinetic energy, T

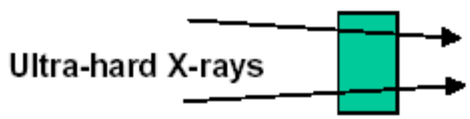
- $\Gamma = \frac{V_{ii}}{T} = \frac{Z^2 e^2}{r_o T}$

  where $r_o \propto \frac{1}{\rho^{1/3}}$

(material from Dick Lee, LLNL/UCB)

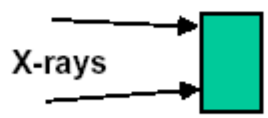
Heat solid-density plasma layers isochorically with nsec ion pulses for equation-of-state measurements

- Foils preheated by hard x-rays



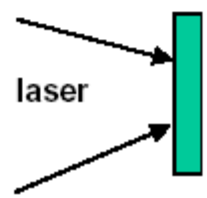
XFEL heating uniform but small volumes (10's of millijoules)

- Supersonically heated foams or low Z materials (thermal x-rays)



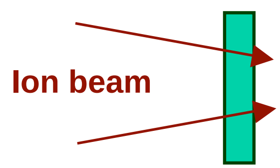
MJ of soft-x-rays available on Z but limited uniformity and limited number of shots

- Shock compressed and heated thin foils



Lasers absorb at critical density << solid density→ large density/ pressure gradients

- Ion heated thin foils

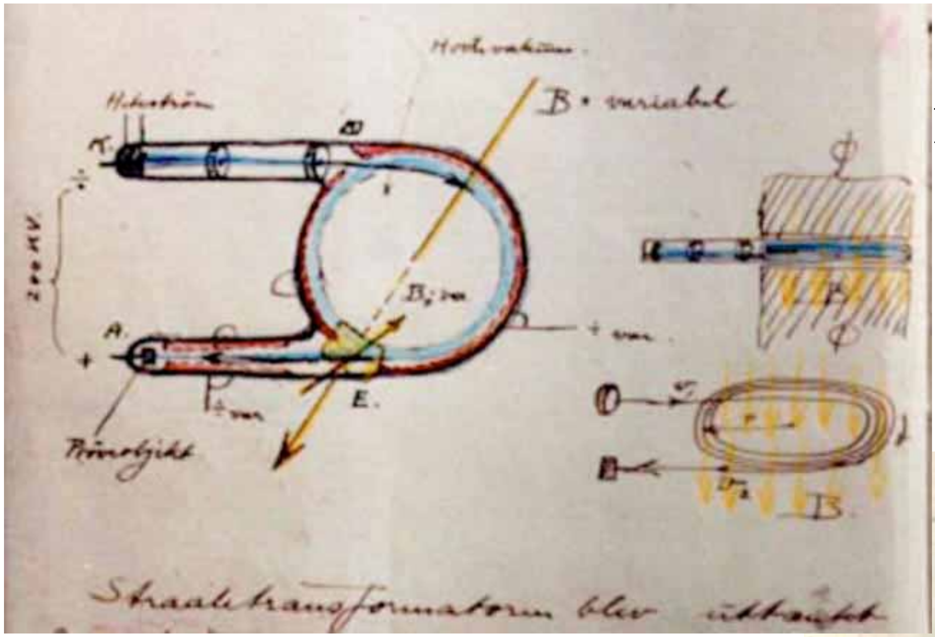


Fast heating of a solid with penetrating ions (dE/dx vs x fairly flat below the Bragg peak) →lower gradients→ more accurate EOS

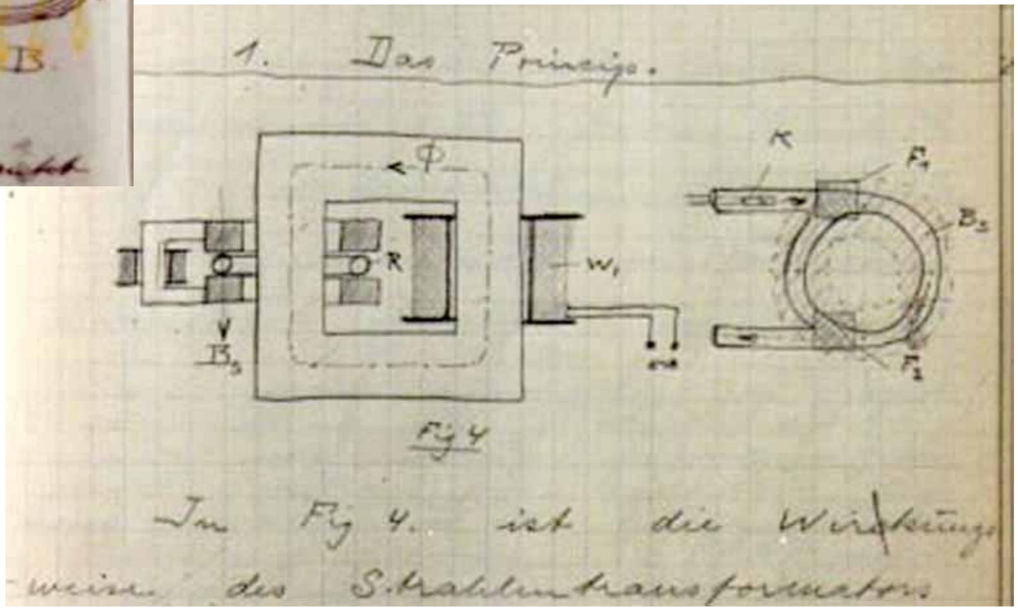
- 100TW lasers create 10-50 mJ of ions for picoseconds → small volumes for diagnostics
- GSI-SIS-100 plans 10-40 kJ of ions @100GeV,100 ns→ large volumes but limited T < few eV

Accelerator technology

Wiederoe’s Ray Transformer for electrons



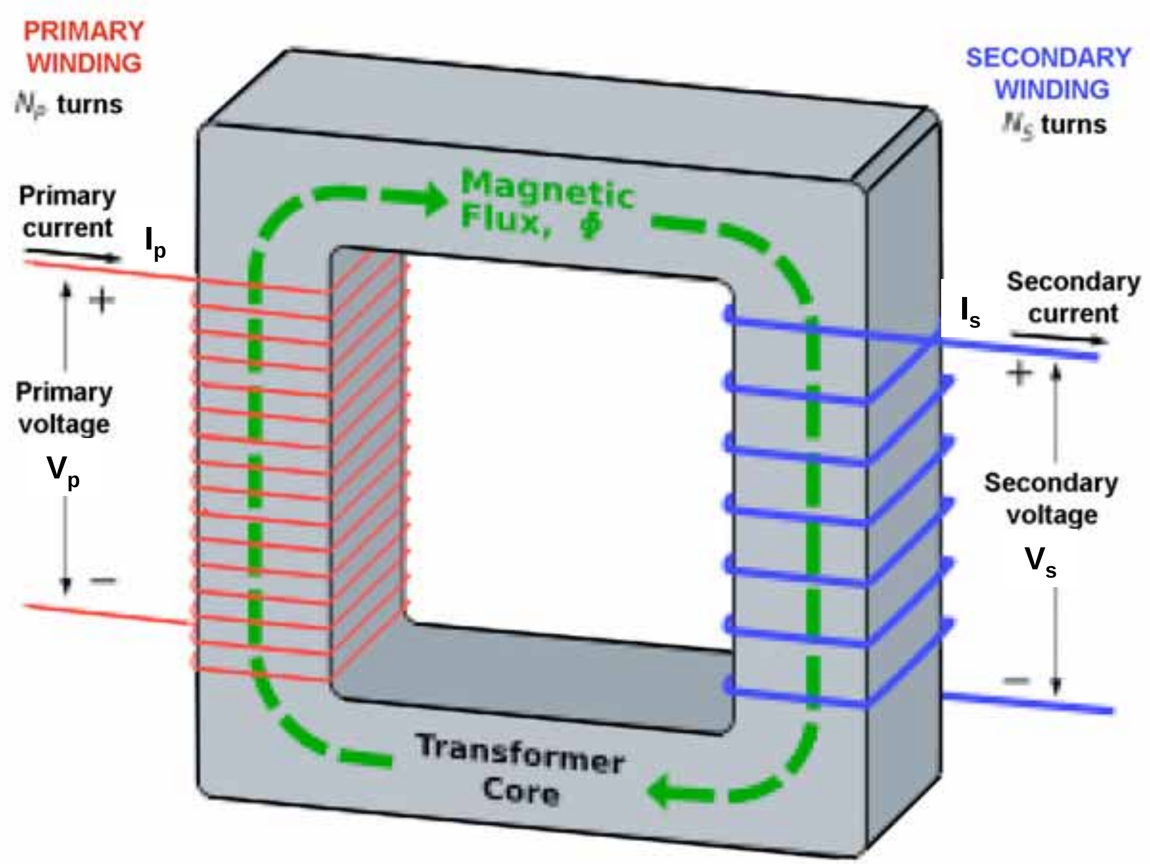
From Wiederoe’s notebooks (1923-’28)



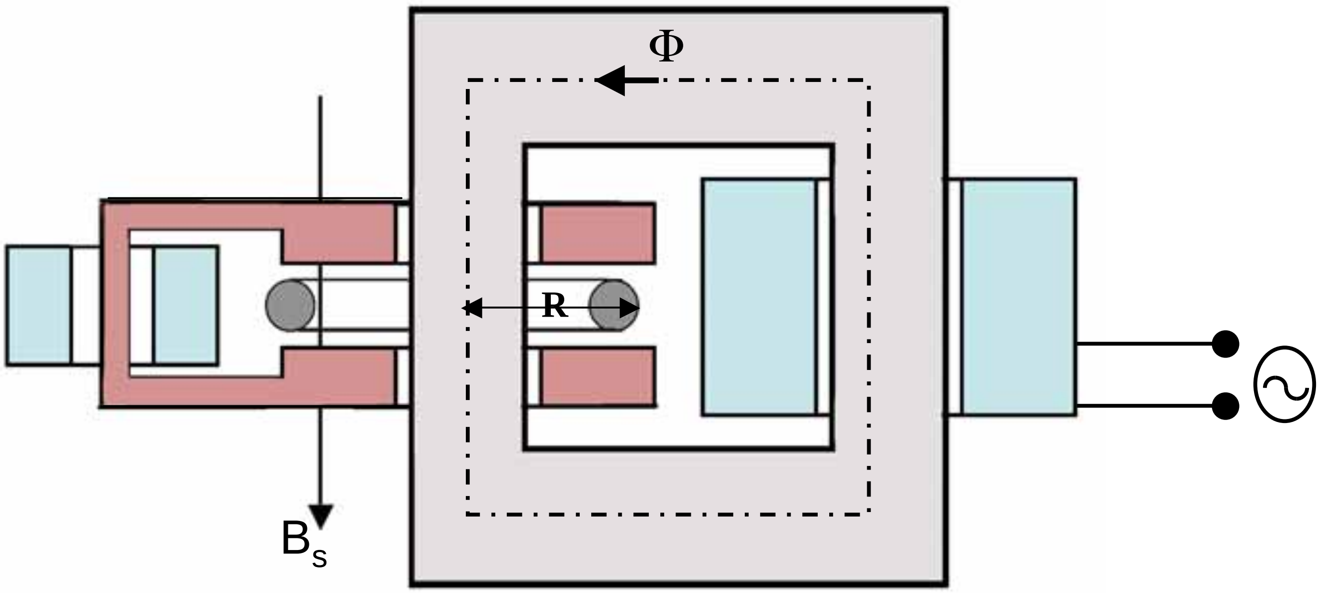
He was dissuaded by his professor from building the ray transformer due to worries about beam-gas scattering

Let that be a lesson to you!

Transformer basics



The ray transformer realized as the Betatron (D. Kerst, 1940)



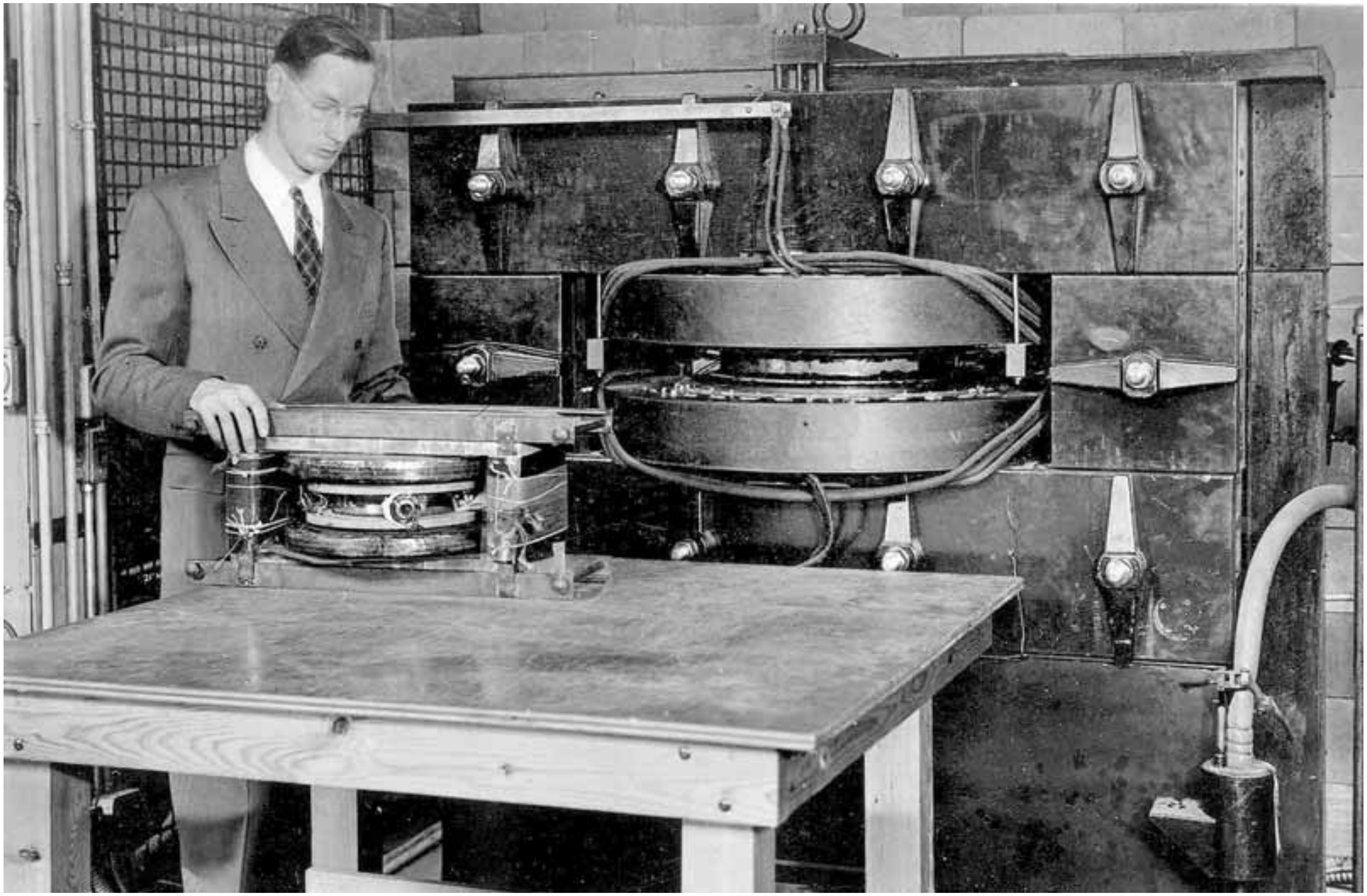
The beam acts as a 1-turn secondary winding of the transformer

Magnetic field energy is transferred directly to the electrons

For the orbit size to remain invariant

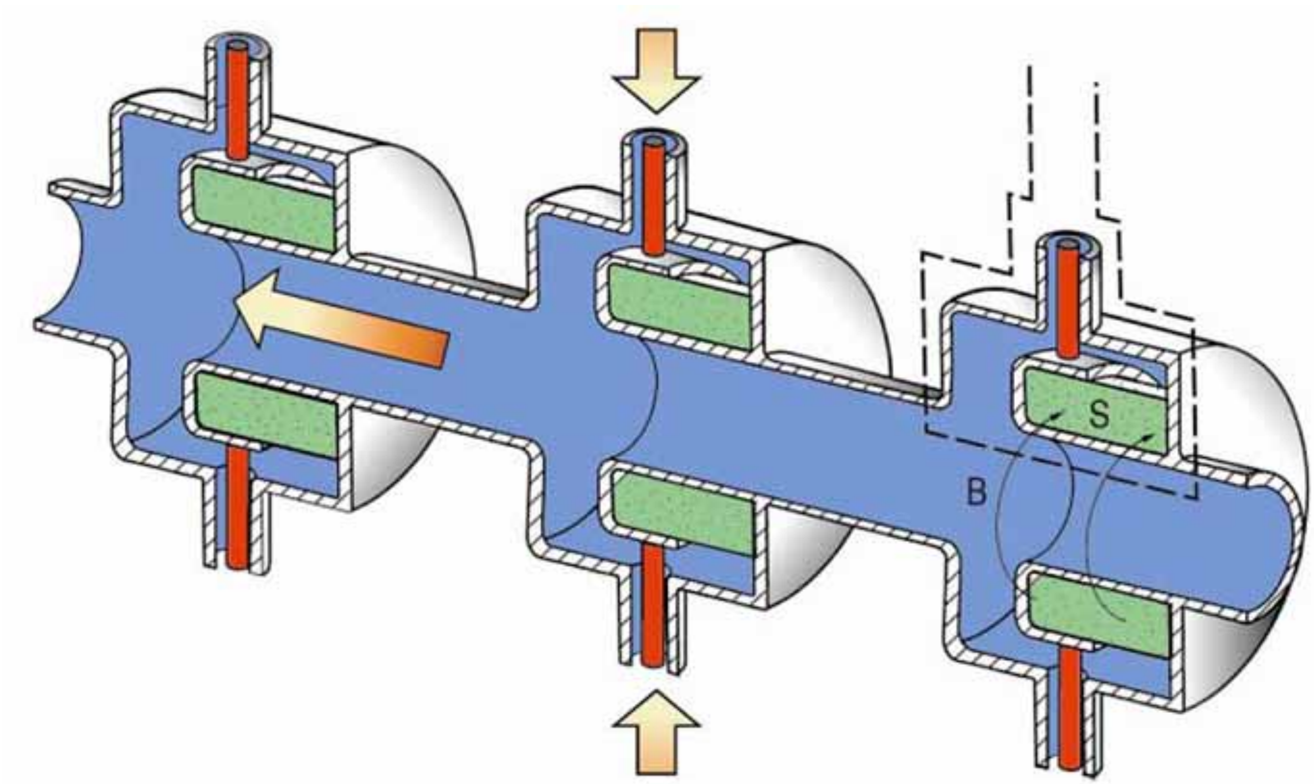
$$\boxed{\dot{\Phi} = 2\pi R^2 \dot{B}_s}$$

Donald Kerst's betatrons



Kerst originally used the phrase, Induction Accelerator

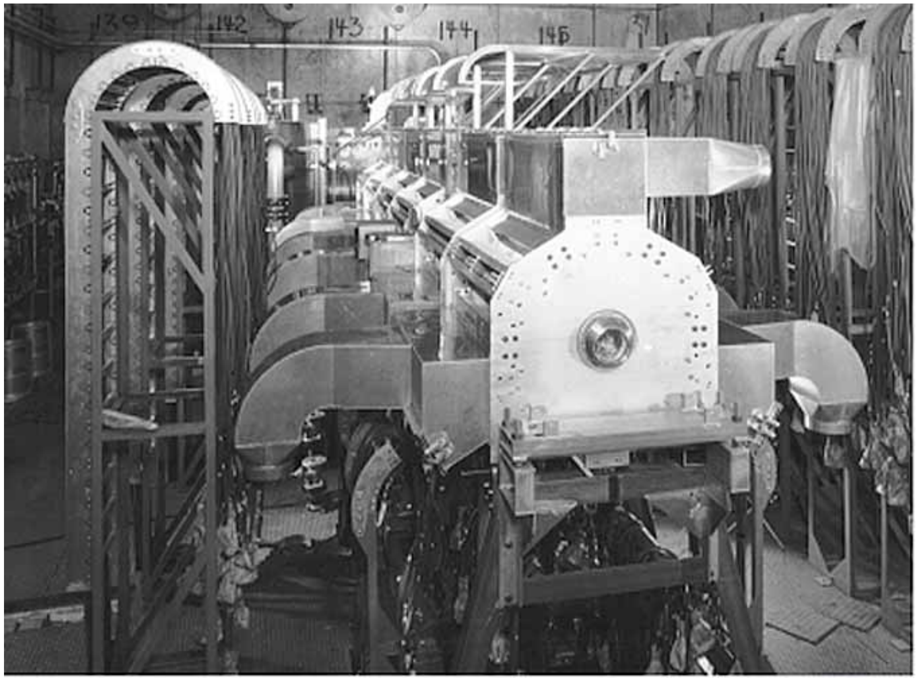
The Linear Betatron: Linear Induction Accelerator



N. Christofilos

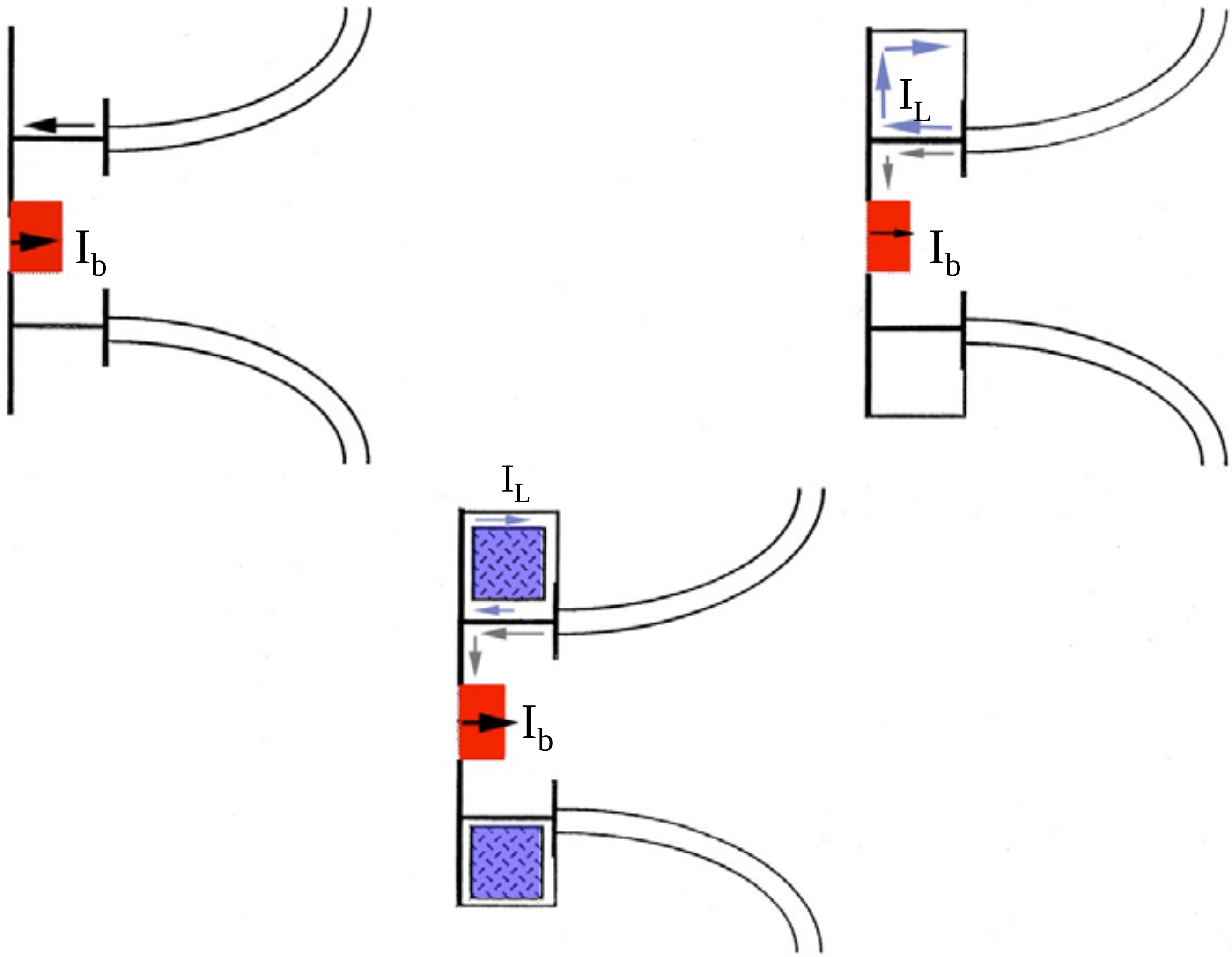
$$\oint_C \mathbf{E}\cdot d\mathbf{l} = -\frac{\partial}{\partial t}\int_S \mathbf{B}\cdot d\mathbf{s}$$

Linear induction accelerators & fusion



Astron-I Induction linac (1963)
& the Astron CTR experiment

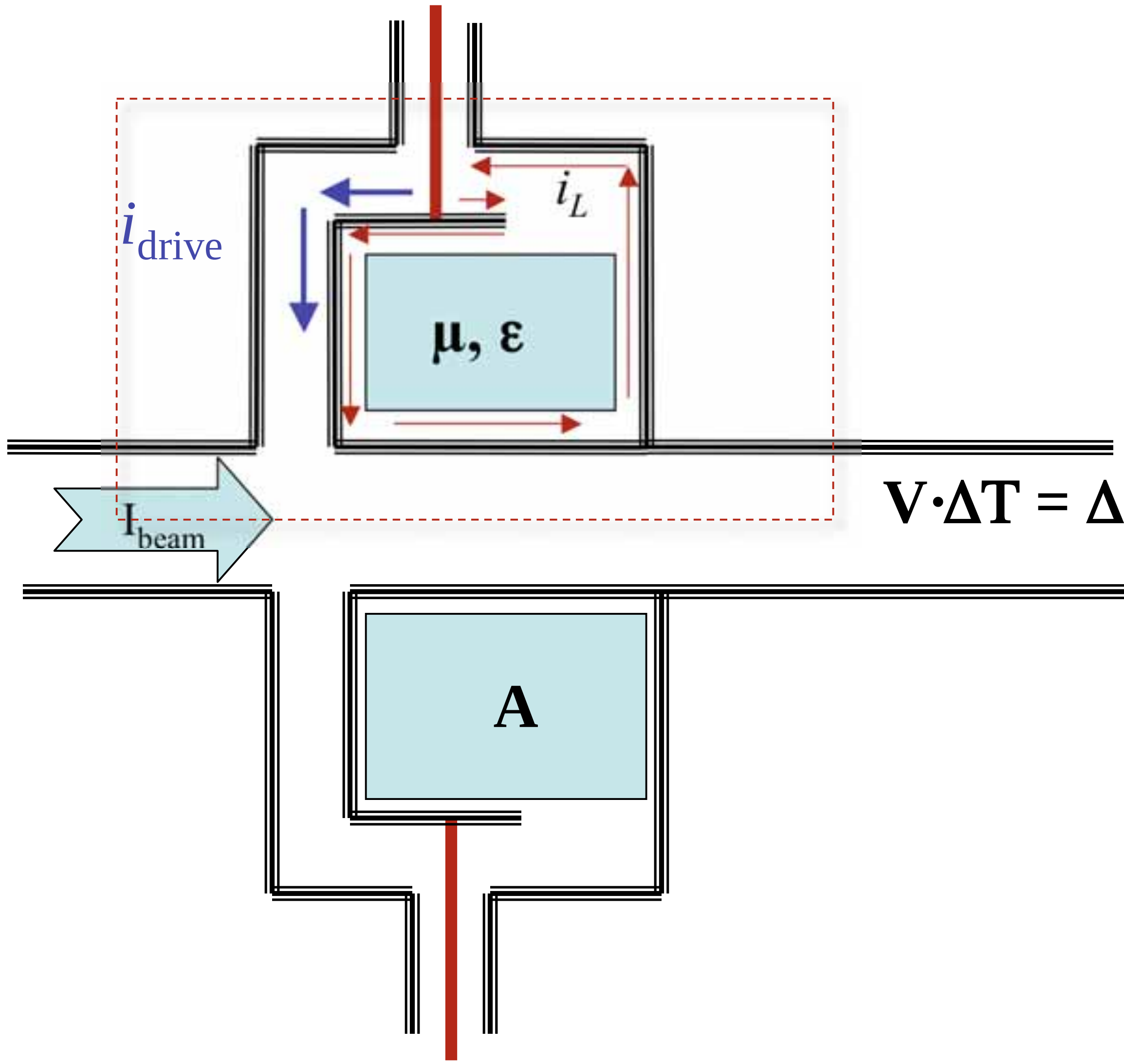
Principle of inductive isolation



Properties of inductive geometry

1. Leakage inductance: $L = (\mu/2\pi) \ln(R_o/R_i)$
   a) $i_L = (V_o/L)t$
2. Ferromagnetic core reduces the leakage current and slows the speed of the shorting wave until the core saturates
3. Load current does not encircle the core
   a) Pulse drive properties not core properties limit I_b
4. Field across the gap is quasi-electrostatic
5. Within the core electrostatic & inductive voltages cancel
   a) The structure is at ground potential

Current flow in the induction core



$$V \cdot \Delta T = \Delta B \cdot A$$

Realistic cross-section of a small induction cell

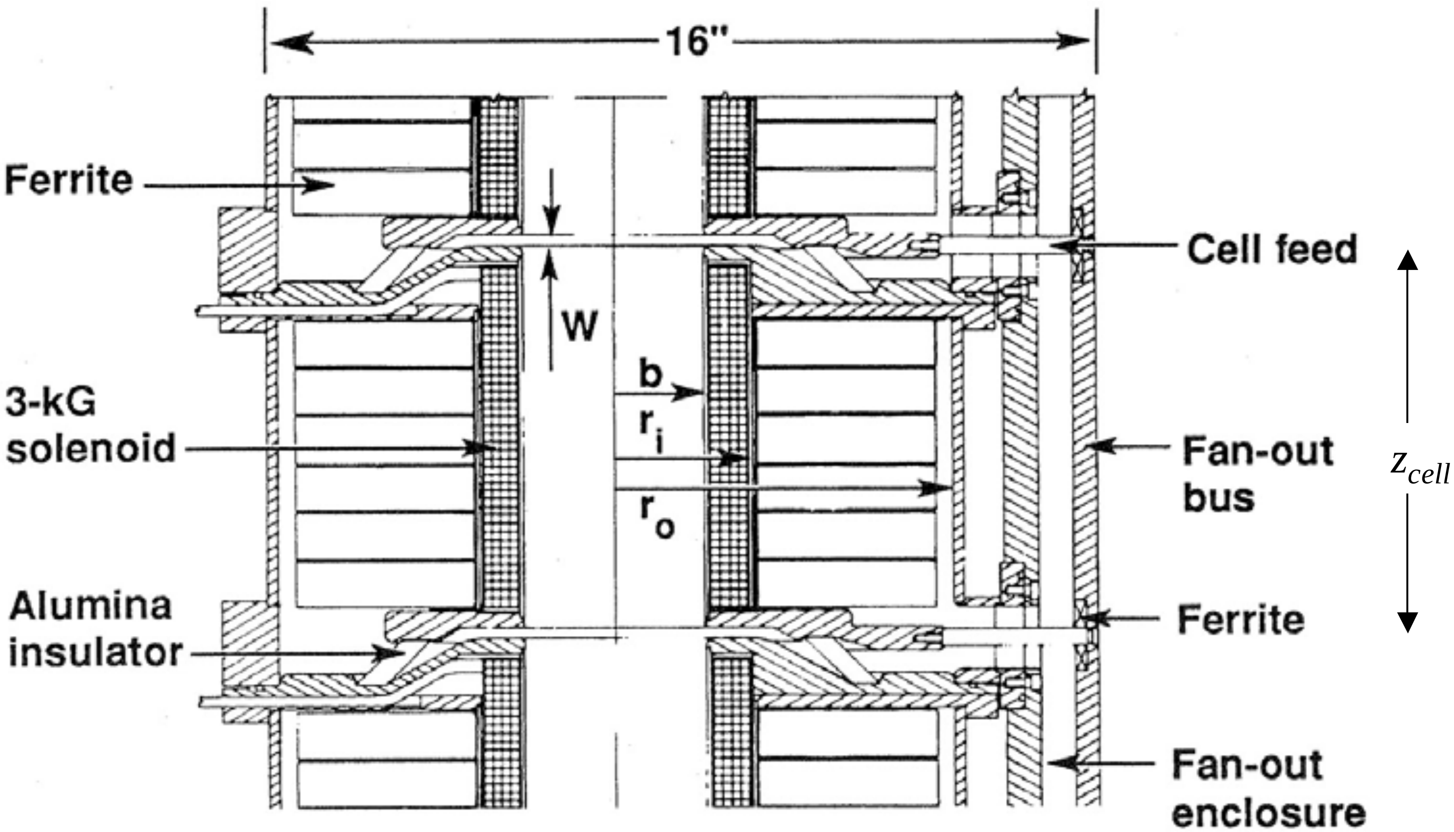
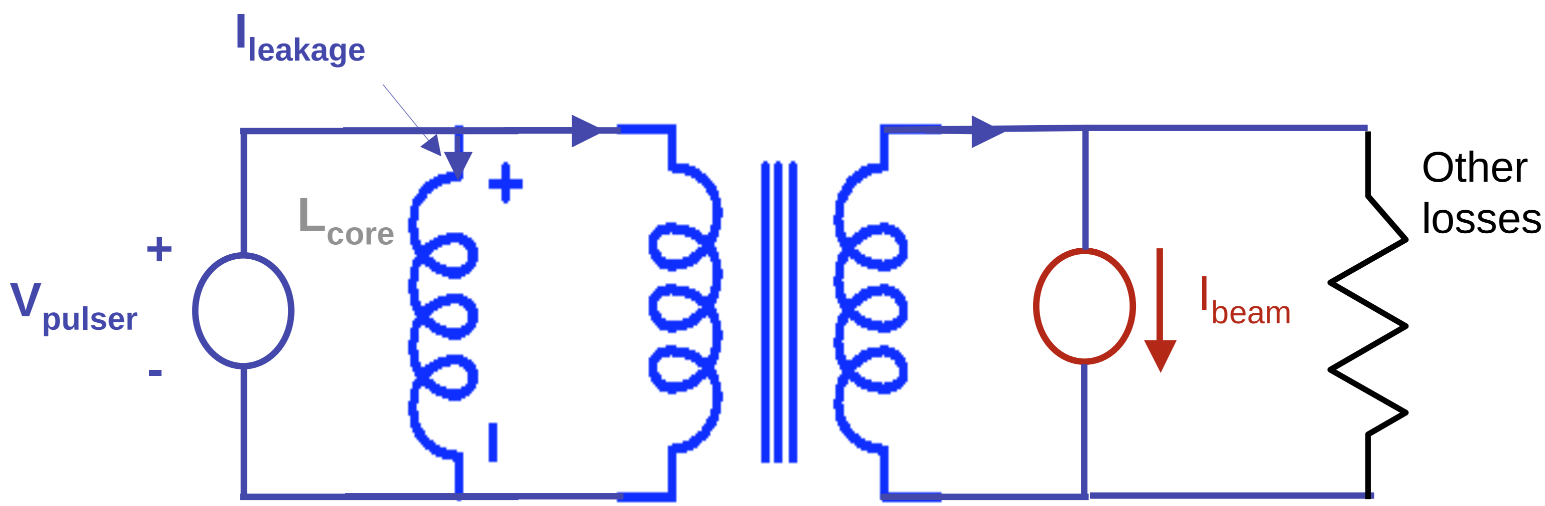


Fig. 5 Typical cross section of low-gamma ten-cell module.

What is the equivalent circuit



Characteristics of coaxial transmission lines

Wave velocity:

$$v_g = 1 \Big/ \sqrt{\mu\varepsilon} = c \Big/ \sqrt{\mu_r \varepsilon_r}$$

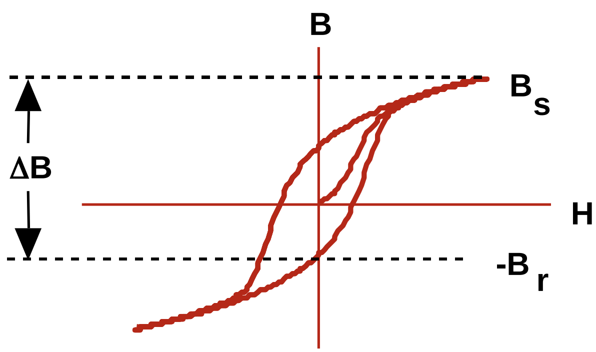
Core impedance:

$$Z_{core} = \sqrt{\mu / \varepsilon} = 120\pi \sqrt{\mu_r / \varepsilon_r} \text{ Ohms}$$

Characteristic impedance:

$$Z = \left(\frac{L}{C}\right)^{1/2} = \frac{Z_{core}}{2\pi} \ln\left(\frac{r_o}{r_i}\right) = \frac{1}{2\pi}\sqrt{\frac{\mu}{\varepsilon}} \ln\left(\frac{r_o}{r_i}\right) = 60\sqrt{\frac{\mu_r}{\varepsilon_r}} \ln\left(\frac{r_o}{r_i}\right)$$

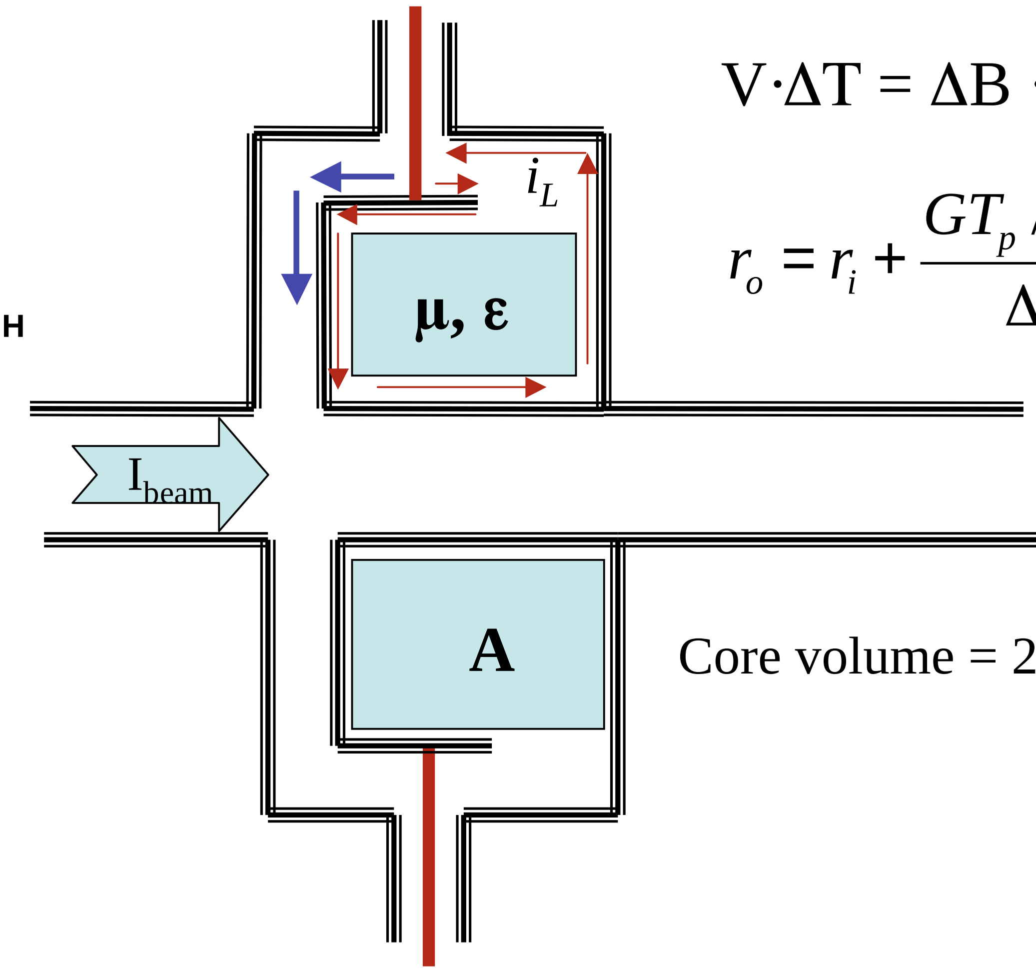
Volt-seconds, gradient (G) & inner radius set the induction core size



Core hysteresis loop

Leakage current magnetizes core

$$i_L = \frac{V}{L_c} t$$

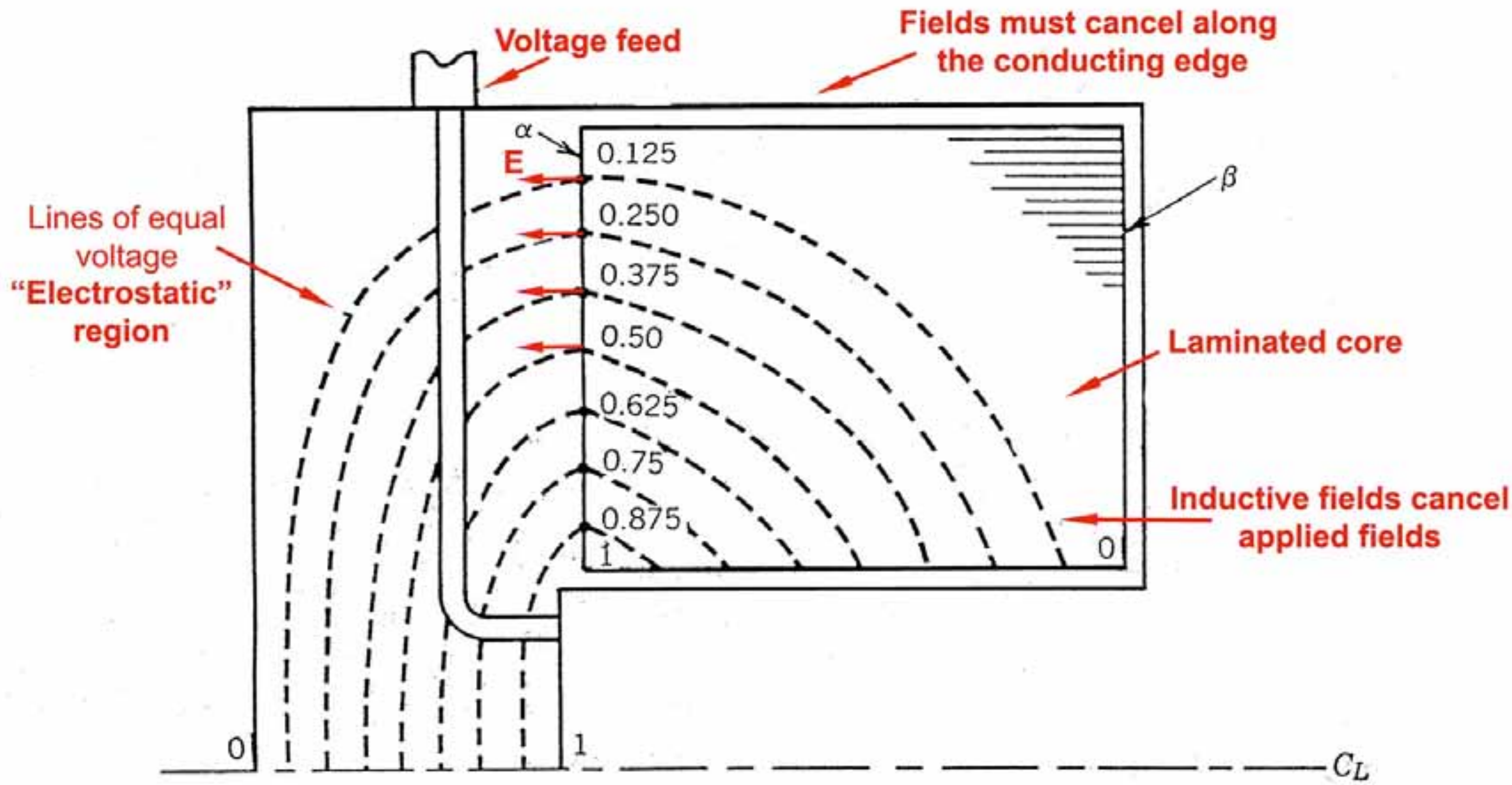


$$V \cdot \Delta T = \Delta B \cdot A \Longrightarrow$$

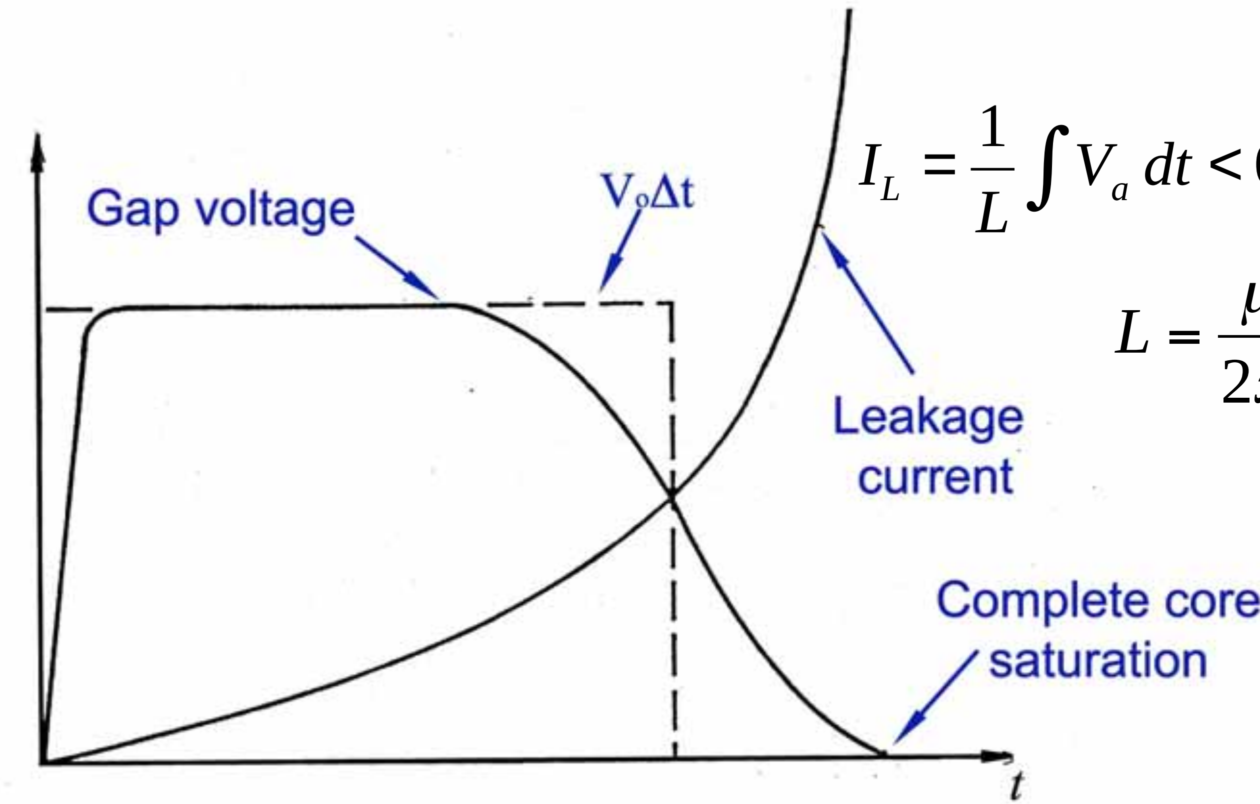
$$r_o = r_i + \frac{G T_p / f_{pack}}{\Delta B}$$

$$\text{Core volume} = 2\pi A(r_o + r_i)$$

Distribution of voltages in induction core
(no local saturation)



Voltage & leakage current behavior at saturation

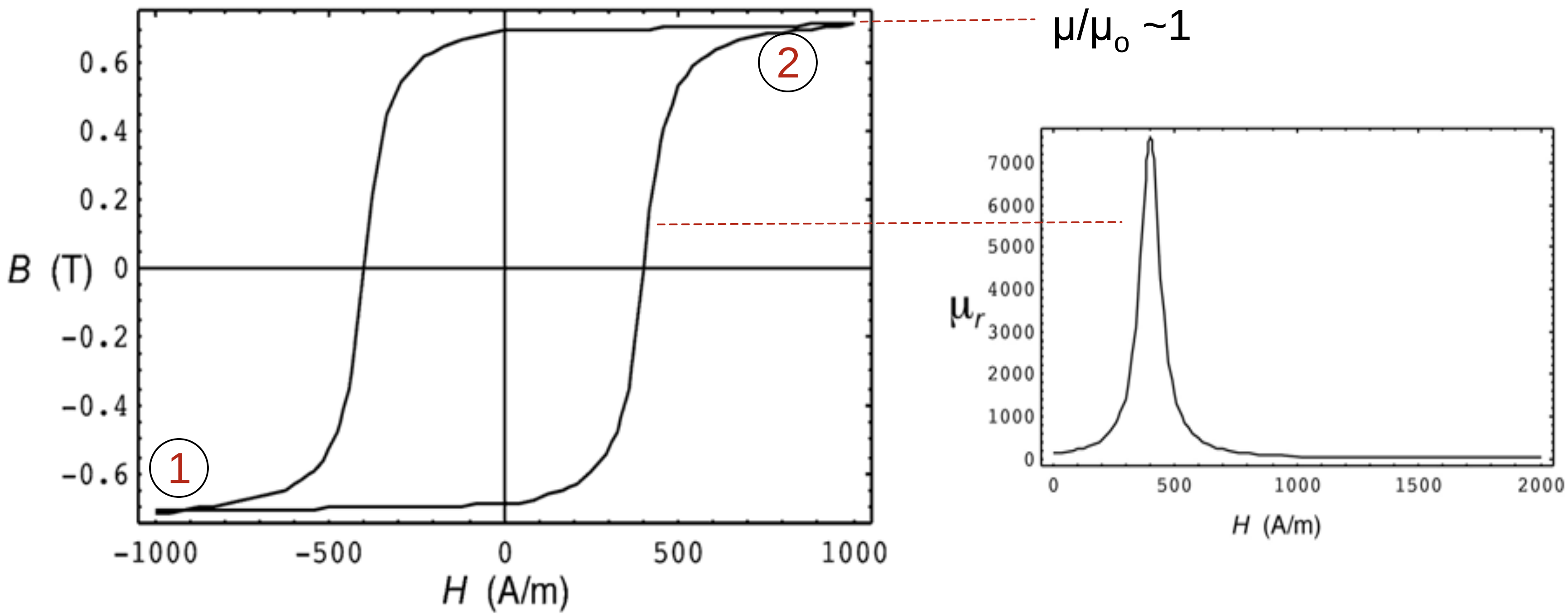


$$I_L = \frac{1}{L}\int V_a\, dt < 0.2 I_{beam}$$

$$L = \frac{\mu}{2\pi} z_{cell} \ln\frac{r_o}{r_i}$$

$$\Re_{core\ loss} = \frac{\pi}{\mu} G T_p^2 \left(\ln\frac{r_o}{r_i}\right)^{-1}$$

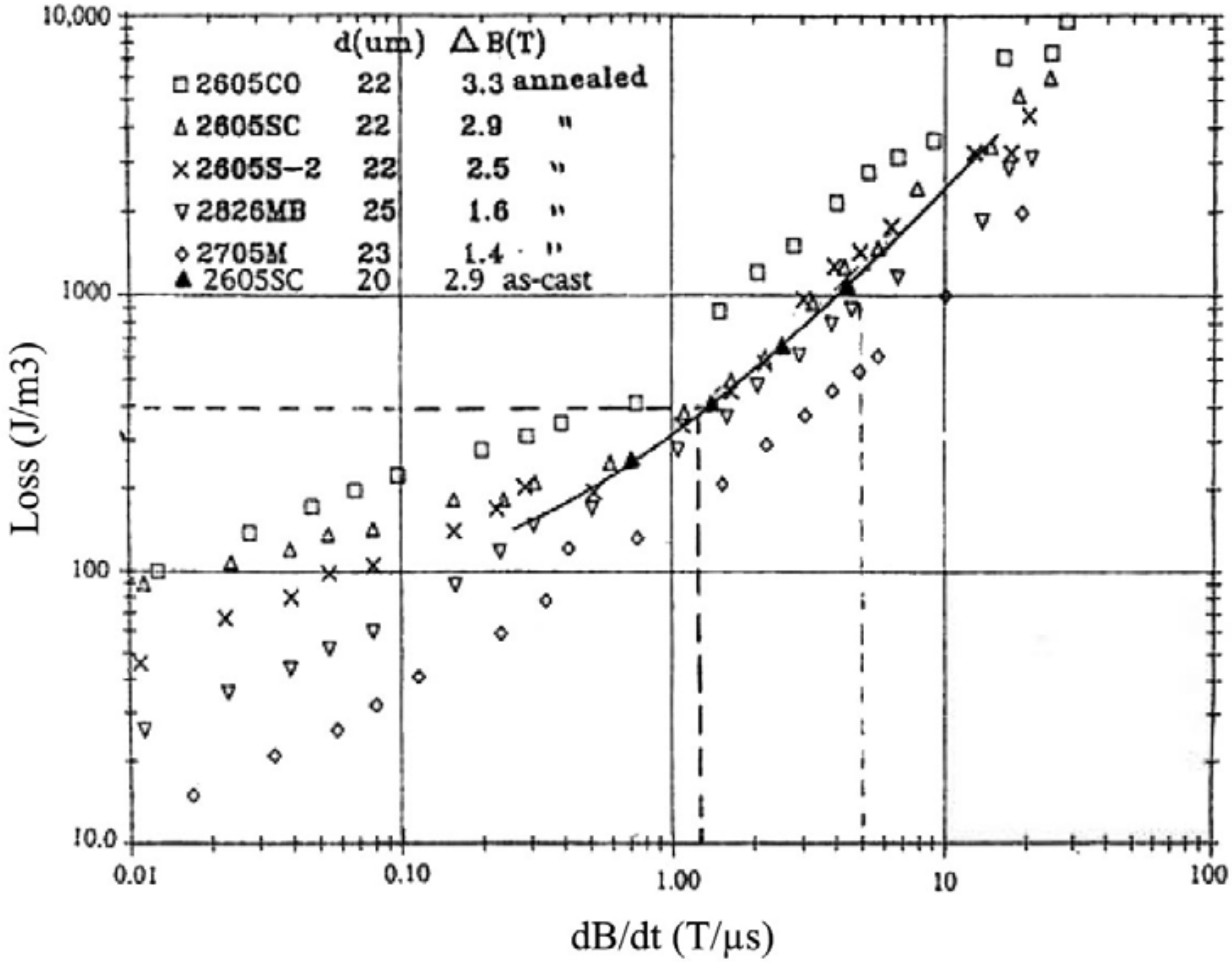
Hysteresis losses in induction cell



B-H hysteresis model curve at τ_{sat}=500 nsec for Co-amorphous

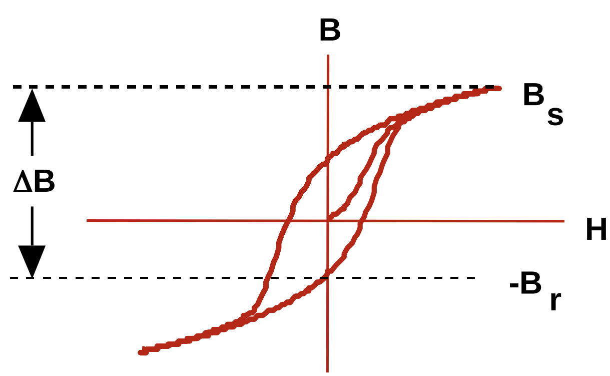
State 1 => State 2: Drive
State 2 => State 1: Reset
Area = Hysteresis loss

Core losses for amorphous materials



Resetting the cores

- Before the core can be pulsed again it must be reset to $-B_r$
- Properties of the reset circuit
  - → Achieve $V\Delta t$ product > B_r+B_s
  - → Supply unidirectional reverse current through the axis of the core
  - → Have high voltage isolation so that the reset circuit does not absorb energy during the drive voltage pulse
    - Depends on the type of pulse forming line used in primary circuit

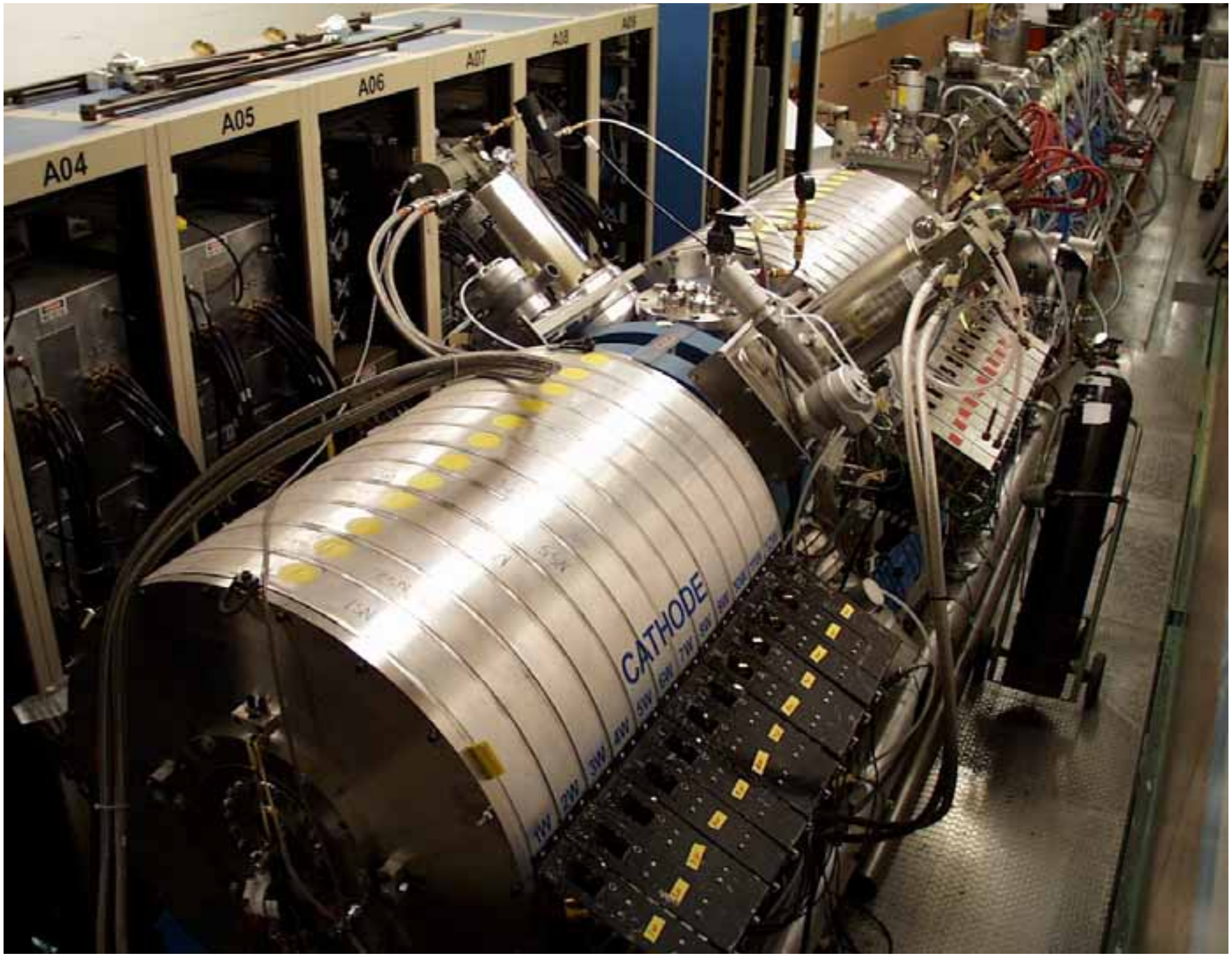


Core hysteresis loop

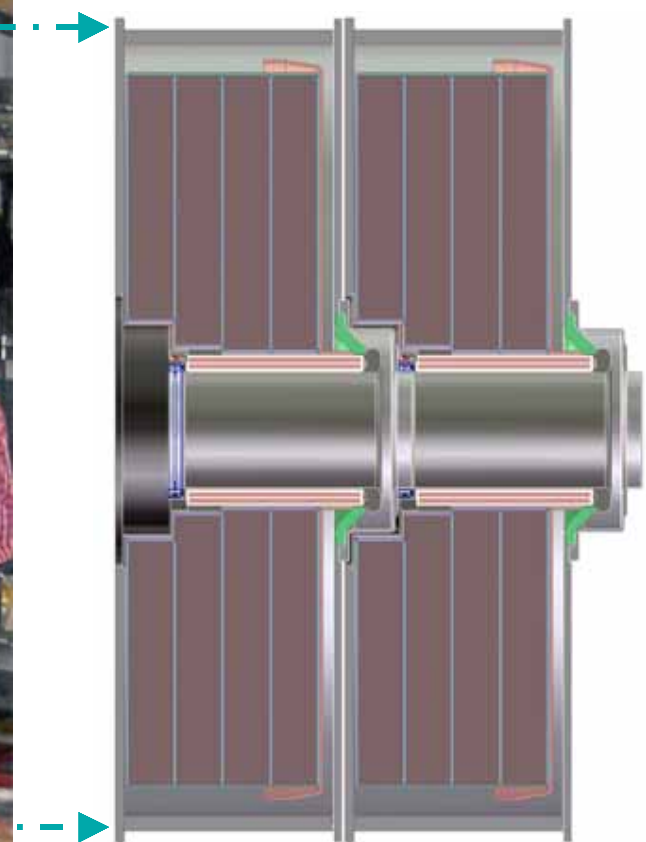
ETA-II Cell Modification

Metglass
replacement core

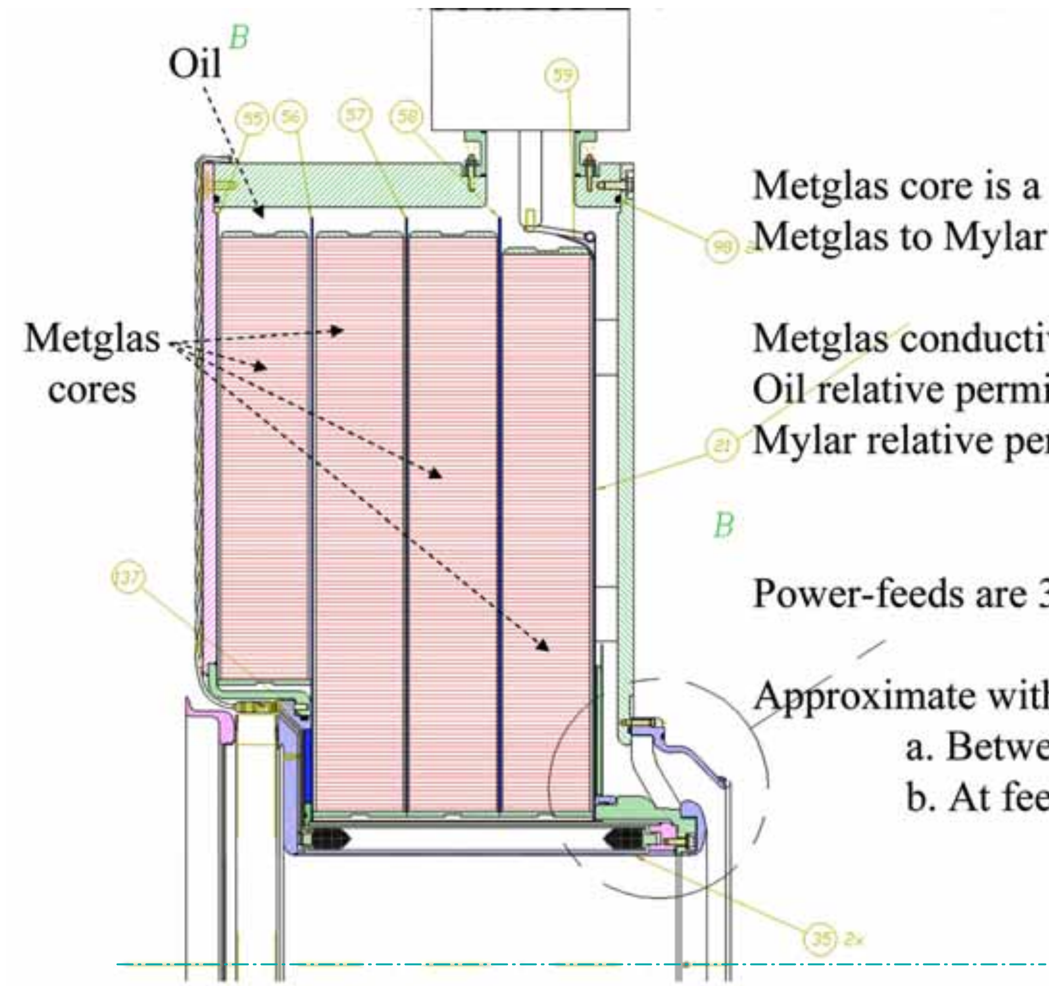
The RTA Injector (1 MeV, 1 KA, 375 ns)



Double 200 kV, 1.6 μs DARHT cell is of the scale needed for HIF



Looking deeper: Cells with large volt-seconds are not simple to engineer



Metglas core is a winding with 3:1 ratio of Metglas to Mylar thickness.

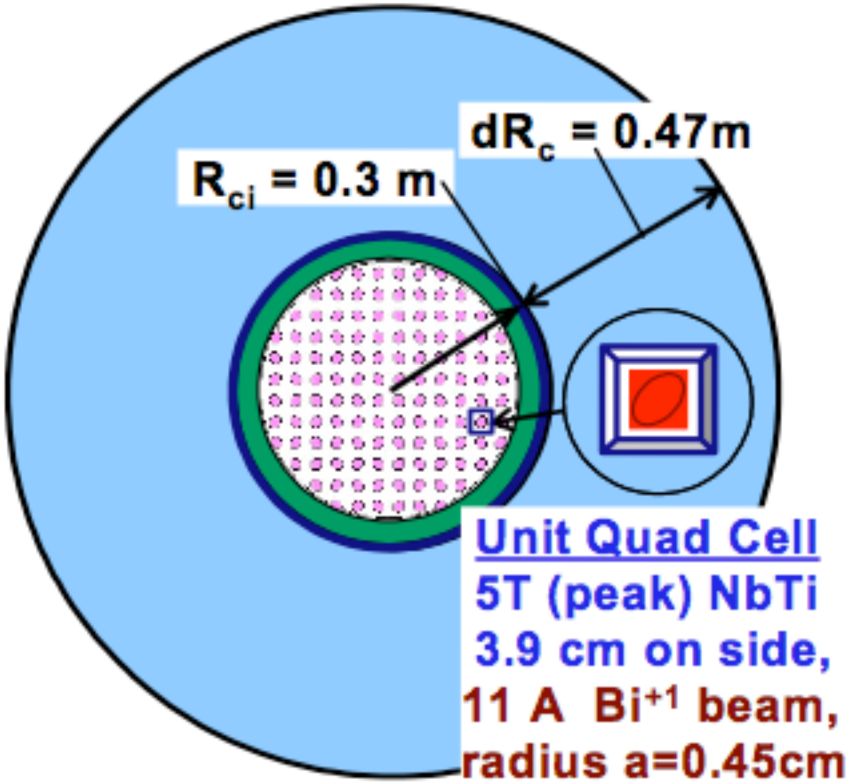
Metglas conductivity: 6.66×10^{16} s^{-1} (cgs)
Oil relative permittivity: 2.25
Mylar relative permittivity: 3.0

Power-feeds are 3D

Approximate with two 2D geometries:

a. Between feeds (e.g., TDC)
b. At feeds

Comparing 1MJ HIF linac driver example cross-sections



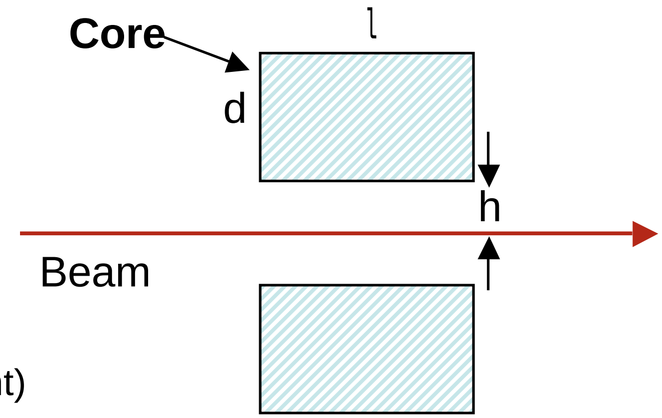
Multi-beam Quad (MQ) driver, an RPD-like design scaled down to produce 1MJ of 4 GeV Bi+ ions in a single pulse.

Modular Solenoid (MS) driver system, one of 40 linacs, to produce 1MJ total of 500 MeV Ar+8 with five pulses per linac.

Why HIF Chose Induction

Induction linacs handle high currents naturally.

$$\text{Efficiency} = \frac{I\,l\,d\,\frac{\Delta \mathbf{B}}{\tau}\,\tau}{\underbrace{I\,l\,d\,\frac{\Delta \mathbf{B}}{\tau}}_{\text{Voltage across gap}}\,\tau + \underbrace{\mathbf{w}}_{\text{Loss function (frequency dependent)}}\,\pi\,\underbrace{l\,d(2h+d)}_{\text{Core volume}}}$$

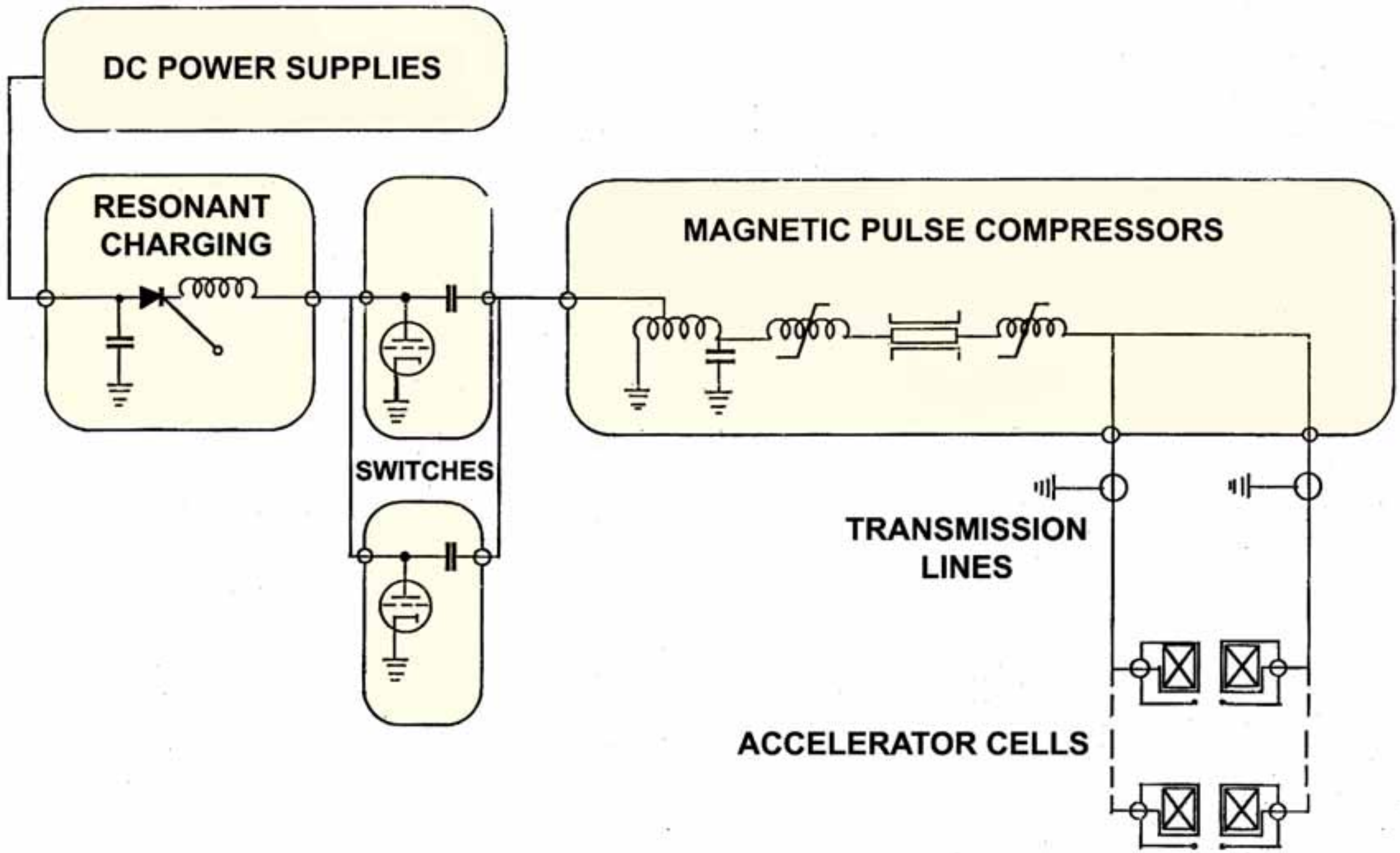


$$\eta_{LIA} = \frac{I\Delta B}{I\Delta B + w\pi(2h+d)}$$

Efficiency increases as current increases

==> Multiple beams within single induction core

Schematic of induction linac power system

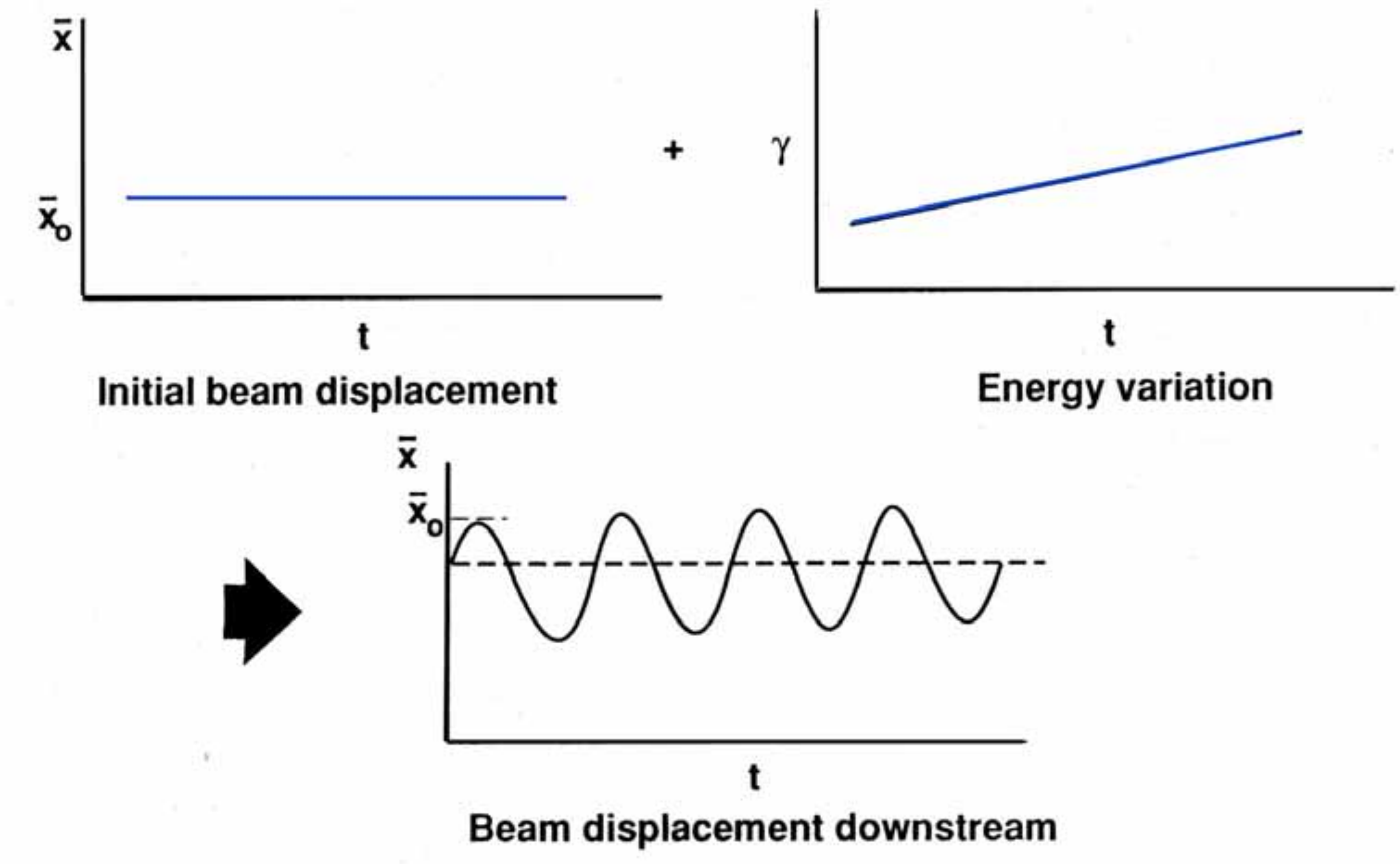


A brief word about instabilities

Beam breakup mode is driven by large currents

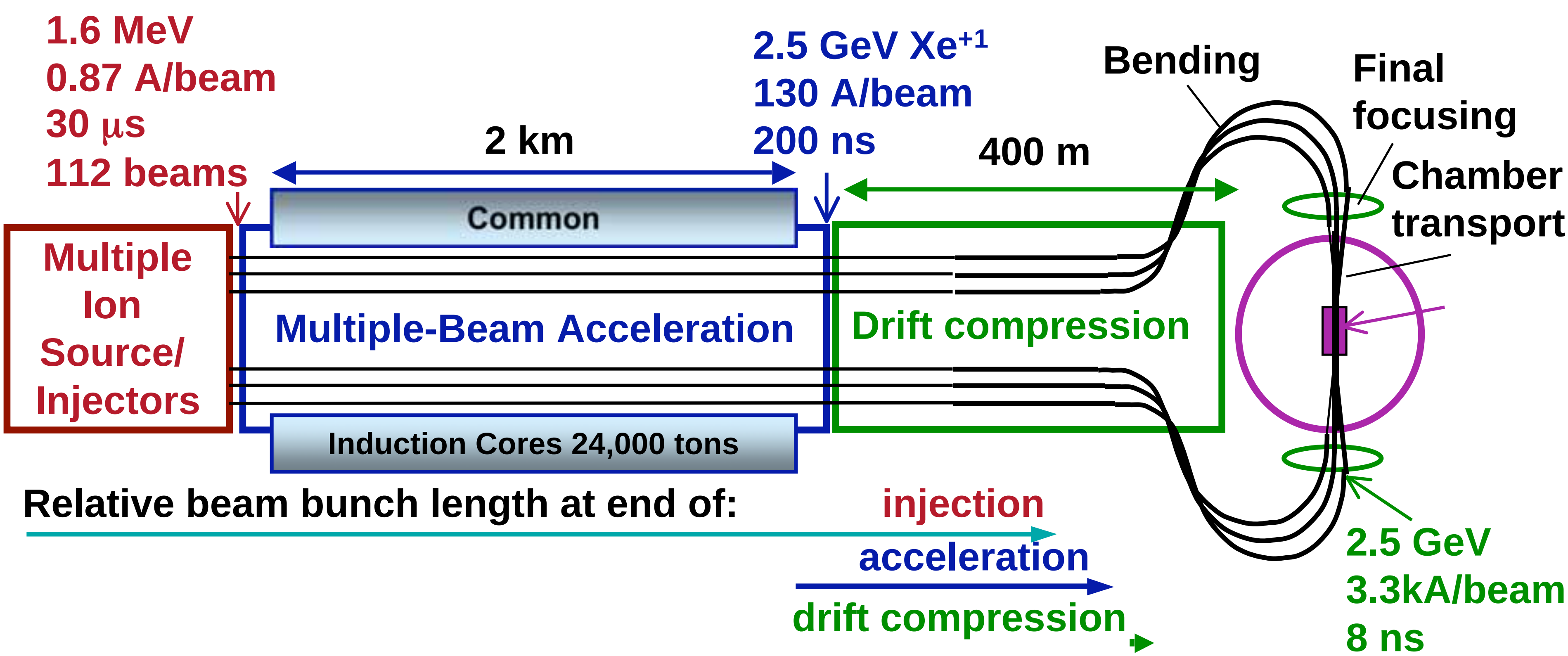
- Off axis beam entering accelerator gap excites dipole (M=1) TM
- Mode has an E_z that can extract energy from the beam
- Mode has a transverse **B** that gives the beam an oscillating transverse impulse
- Oscillating transverse impulse develops into transverse displacement in B_z field between gaps
- Beam enters next gap with a larger displacement than at previous gap-thus displacement grows

Misalignment and energy sweep lead to "corkscrew" increase in emittance



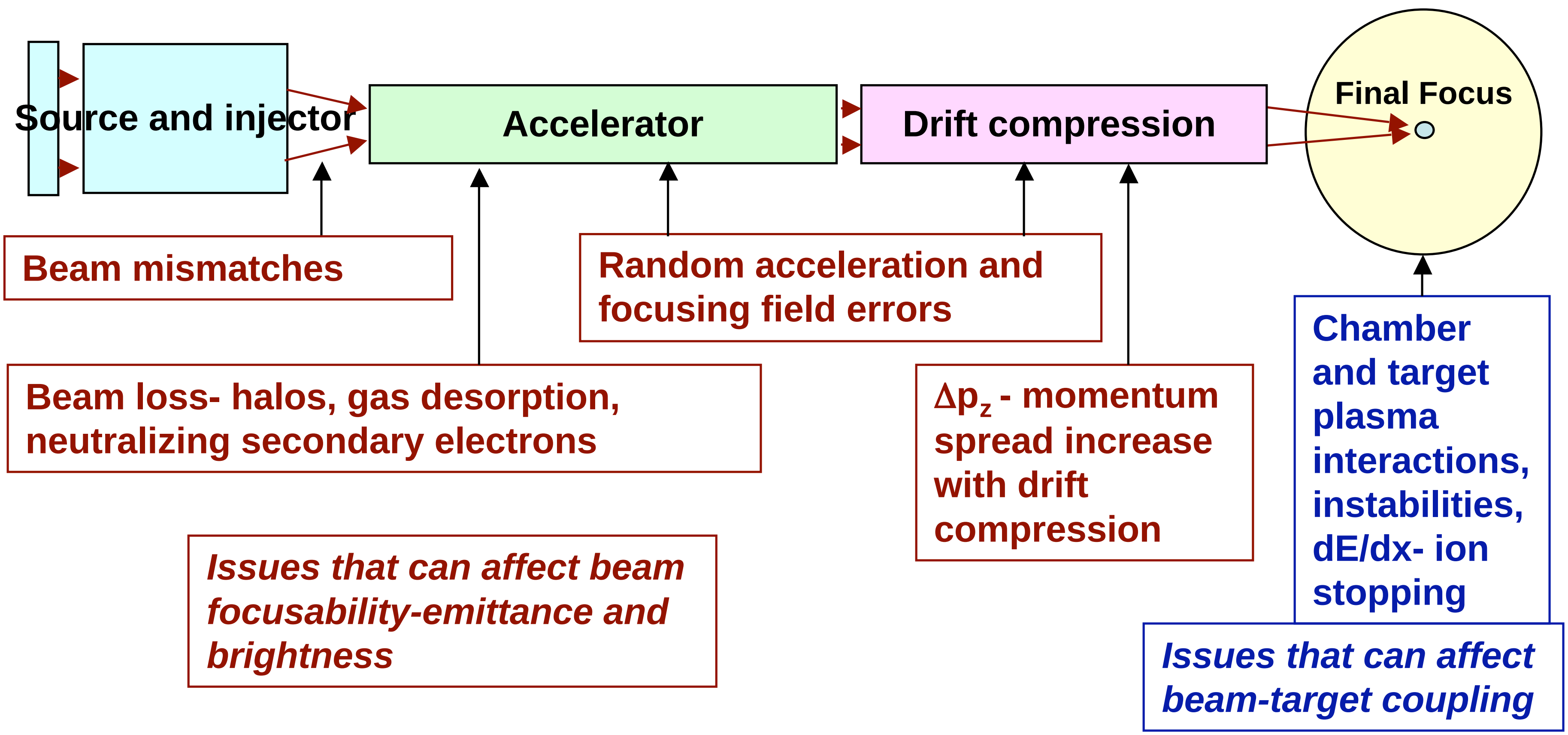
Bunch compression
&
Progress in HIF beam physics

Bunch length compression is integral part of HIF concept



Within accelerator, average induction pulse ~300 ns
Target requires pulse duration of ~10 ns

How much is emittance degraded from source to target? how is coupling to targets affected?



Recent VNL experiments addressed key issues affecting beam brightness

Source-Injector test facility

(STS)

Neutralized Transport Experiment

(NTX)

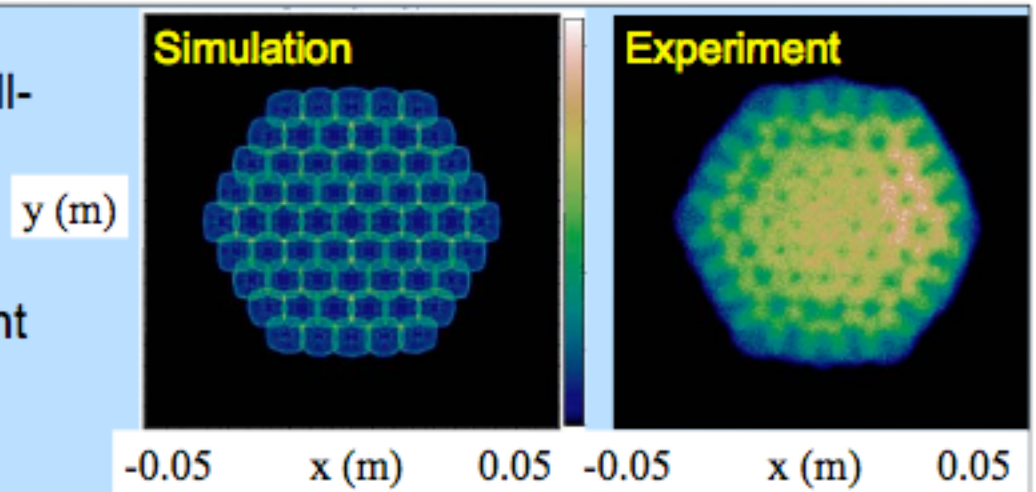
High Current Experiment

(HCX)

Merging beamlet injector experiments on STS-500 validated the concept of this compact, high current source

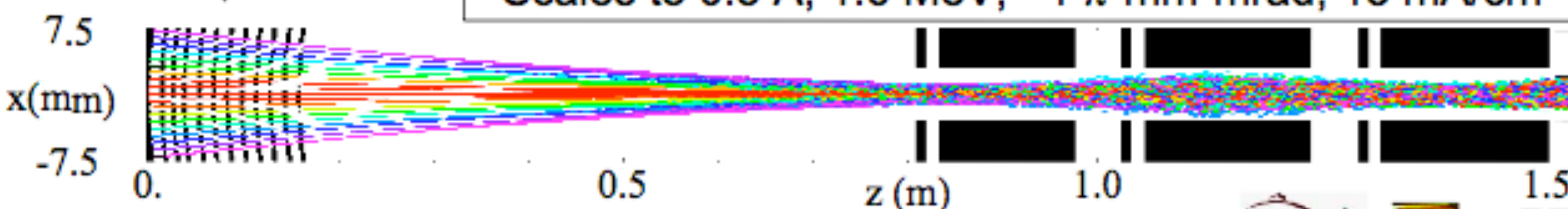
- Monolithic solid sources suffer from poor scaling vs. size at high currents
- This new concept circumvents the problem via use of many small, low-current sources

From a full-gradient (parallel-beamlet) experiment



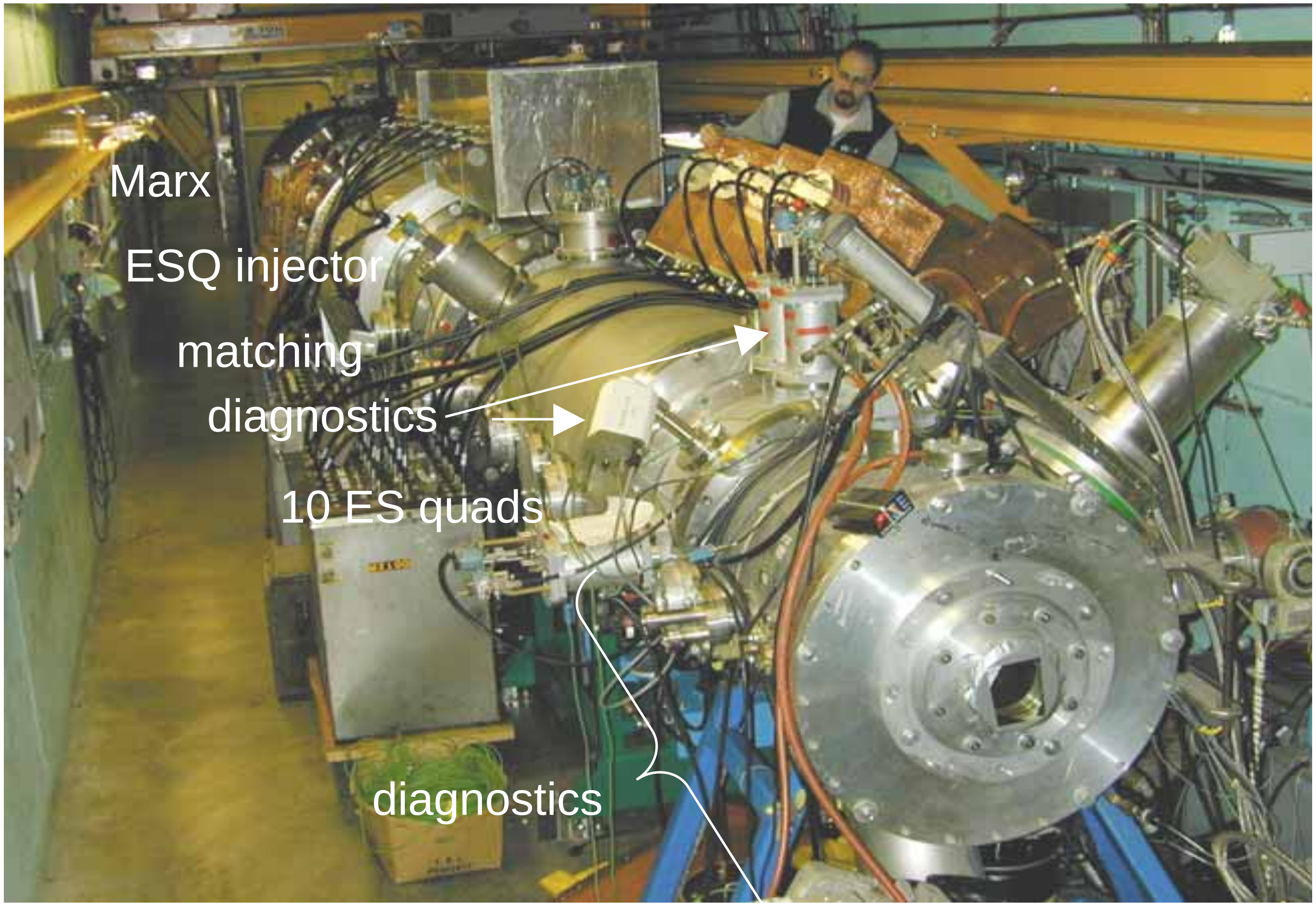
From scaled merging experiment:

- Obtained emittances comparable to simulation
- Effects of “dirty” physics (electrons, charge exchange) were minimal
- Scales to 0.5 A, 1.6 MeV, ~1 π-mm-mrad, 13 mA/cm^2

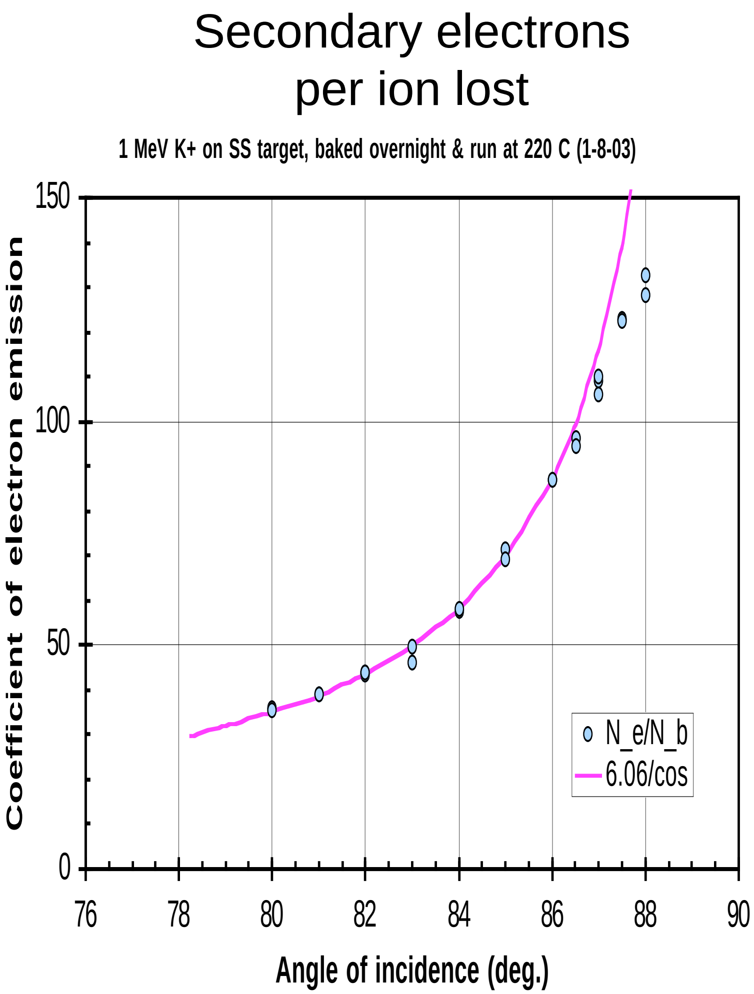


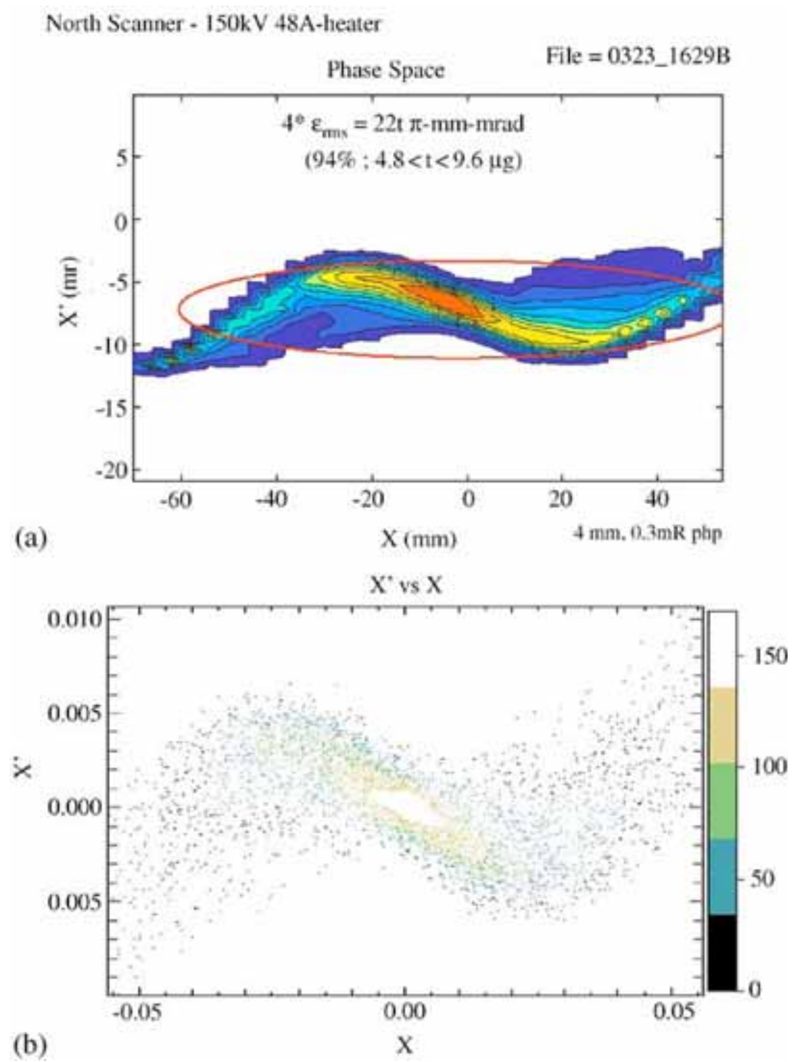
High Current Experiment (HCX) studies high current transport

Transport: aperture limits, electrons, gas effects, halo formation, steering



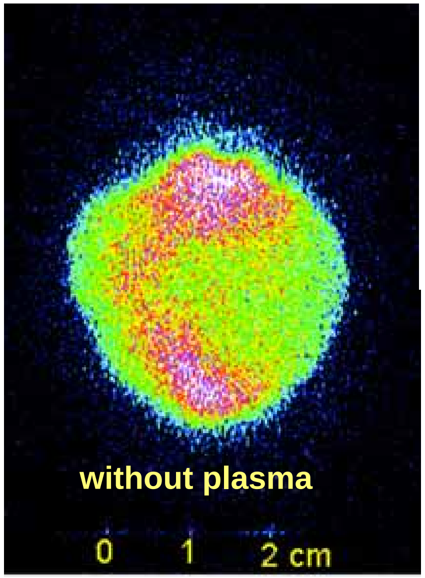
HCX experimental results

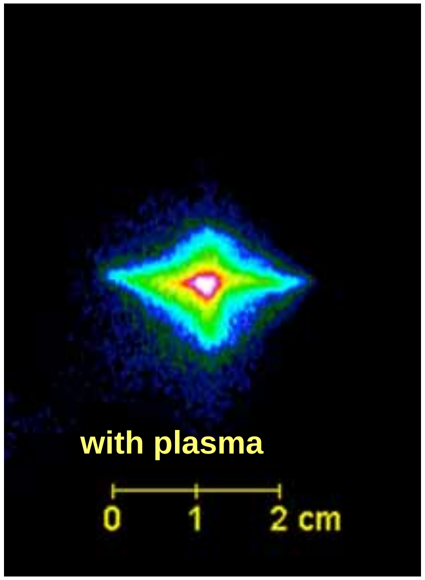




Neutralized Transport Experiment (NTX) tests focusing & compression

Focusing: aberration control, plasma control techniques and diagnostics

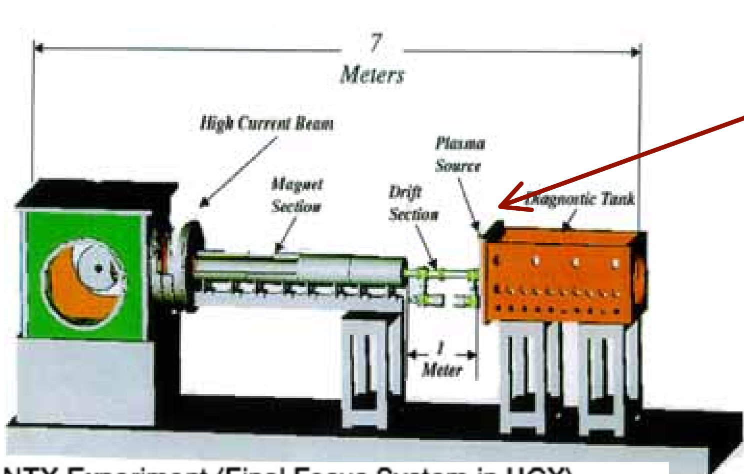


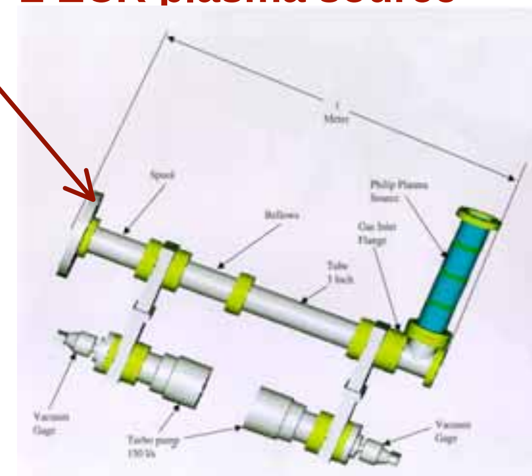


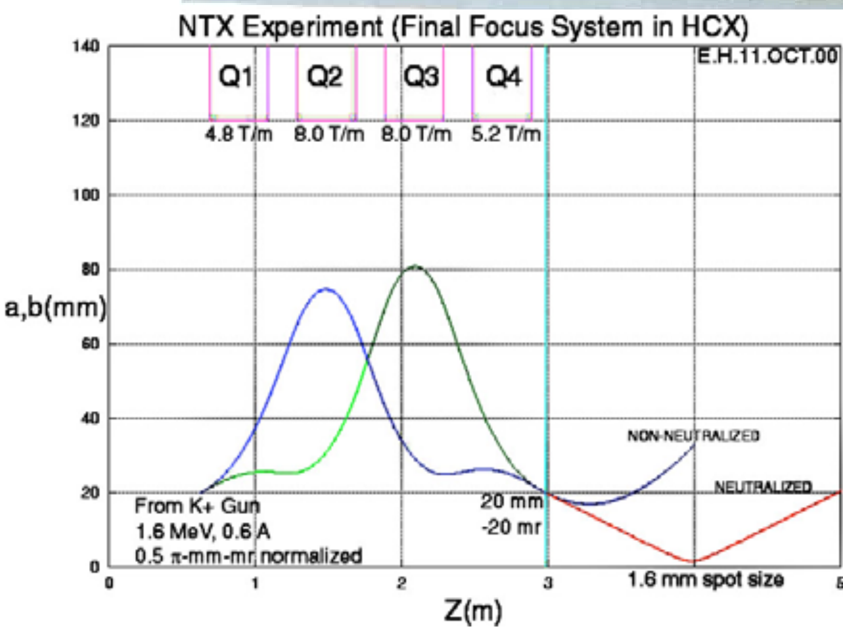
Focal spot images

Neutralized Transport Experiment (NTX): final focus with plasma neutralization

PPPL ECR plasma source



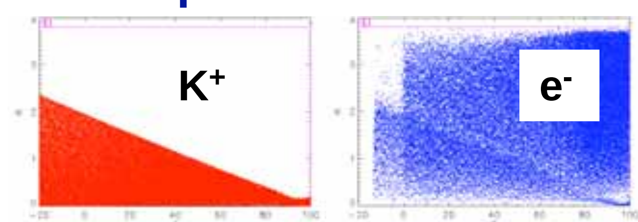




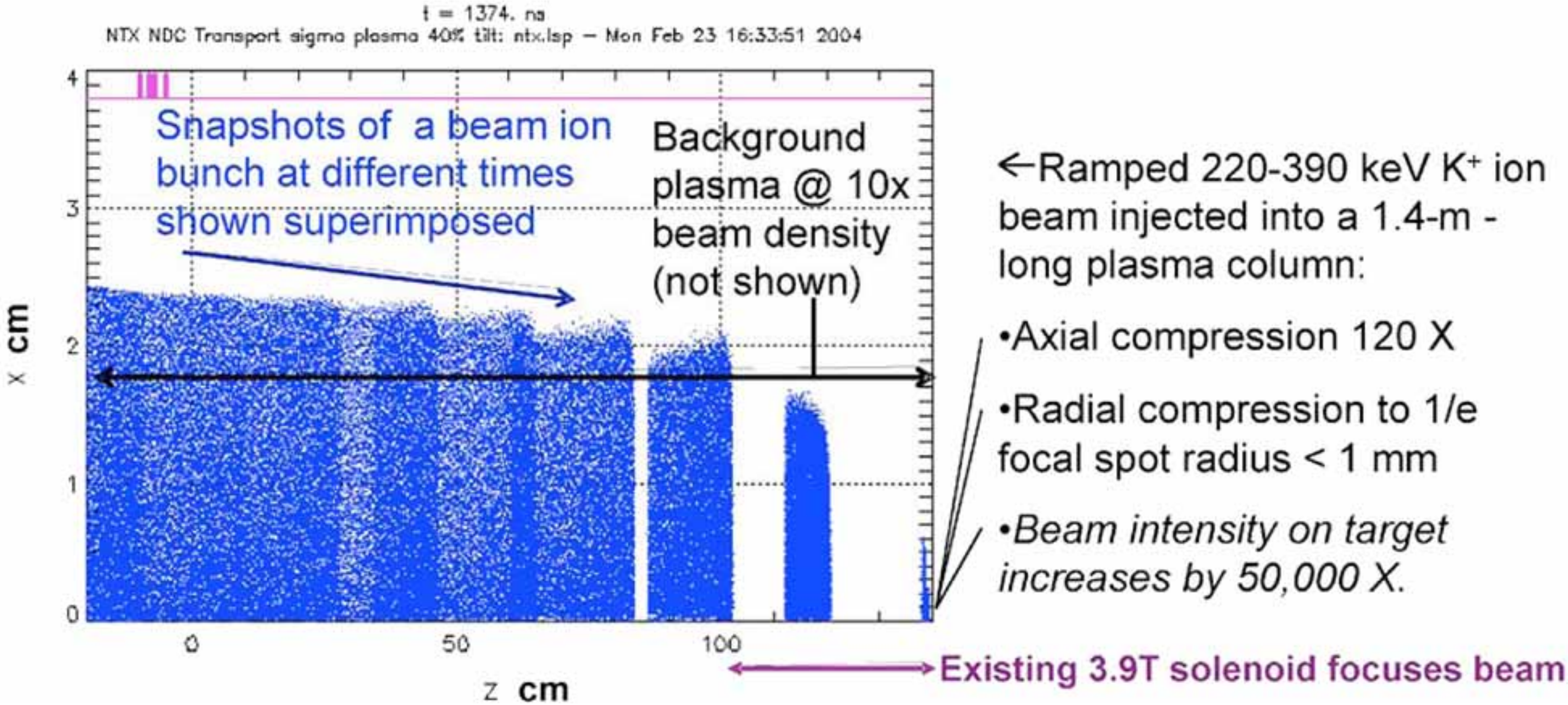
NTX gun current = 80mA @ 0.4 MeV very

Measured emittance $\varepsilon_N \leq 0.1\,\pi$ mm-mr.

Simulations predict 99% neutralization



Bunch compression on NTX

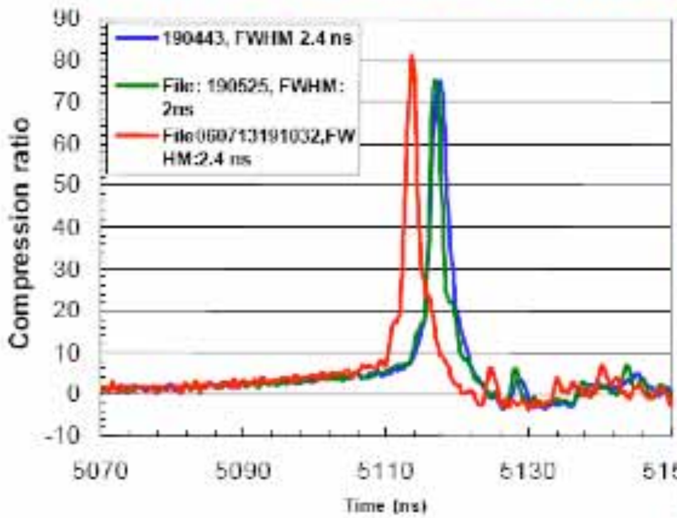


←Ramped 220-390 keV K^+ ion beam injected into a 1.4-m - long plasma column:

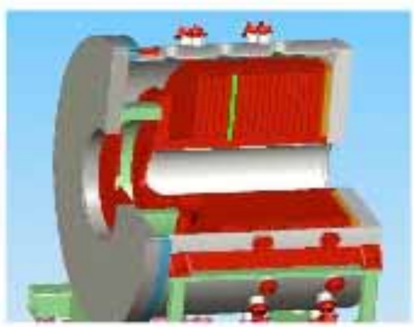
- Axial compression 120 X
- Radial compression to 1/e focal spot radius < 1 mm
- *Beam intensity on target increases by 50,000 X.*

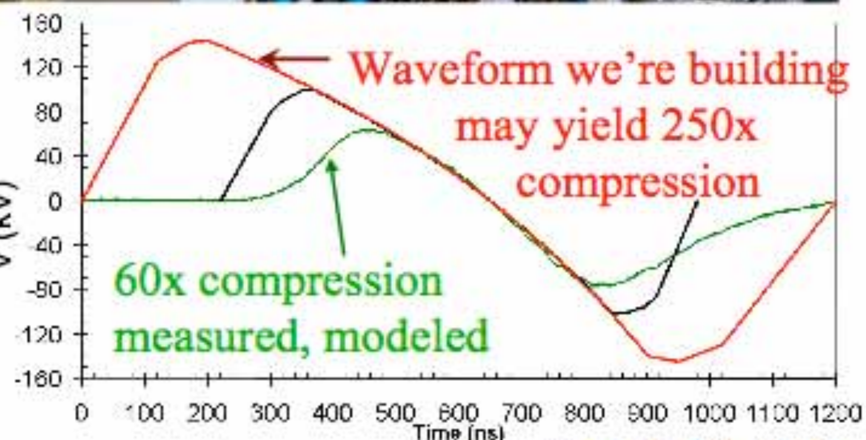
The neutralized drift compression experiment (NDCX-I) continues to improve longitudinal compression of intense neutralized ion beams

Shorter pulses (2.4 ns) obtained with new Ferro-electric plasma source

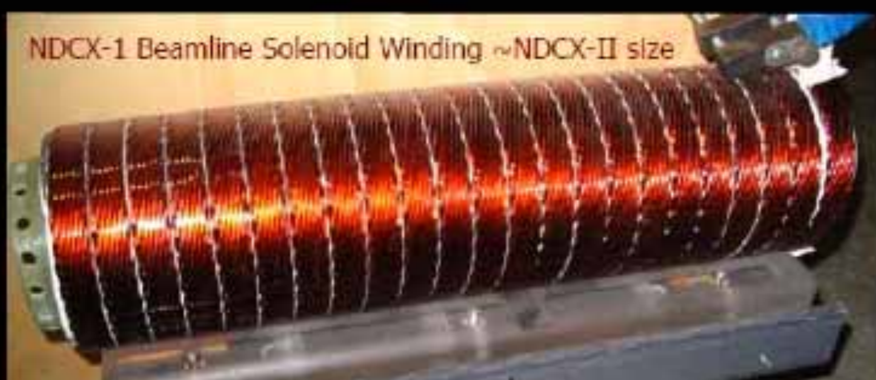


Simulations predict higher compression with new induction bunching module to be installed this summer



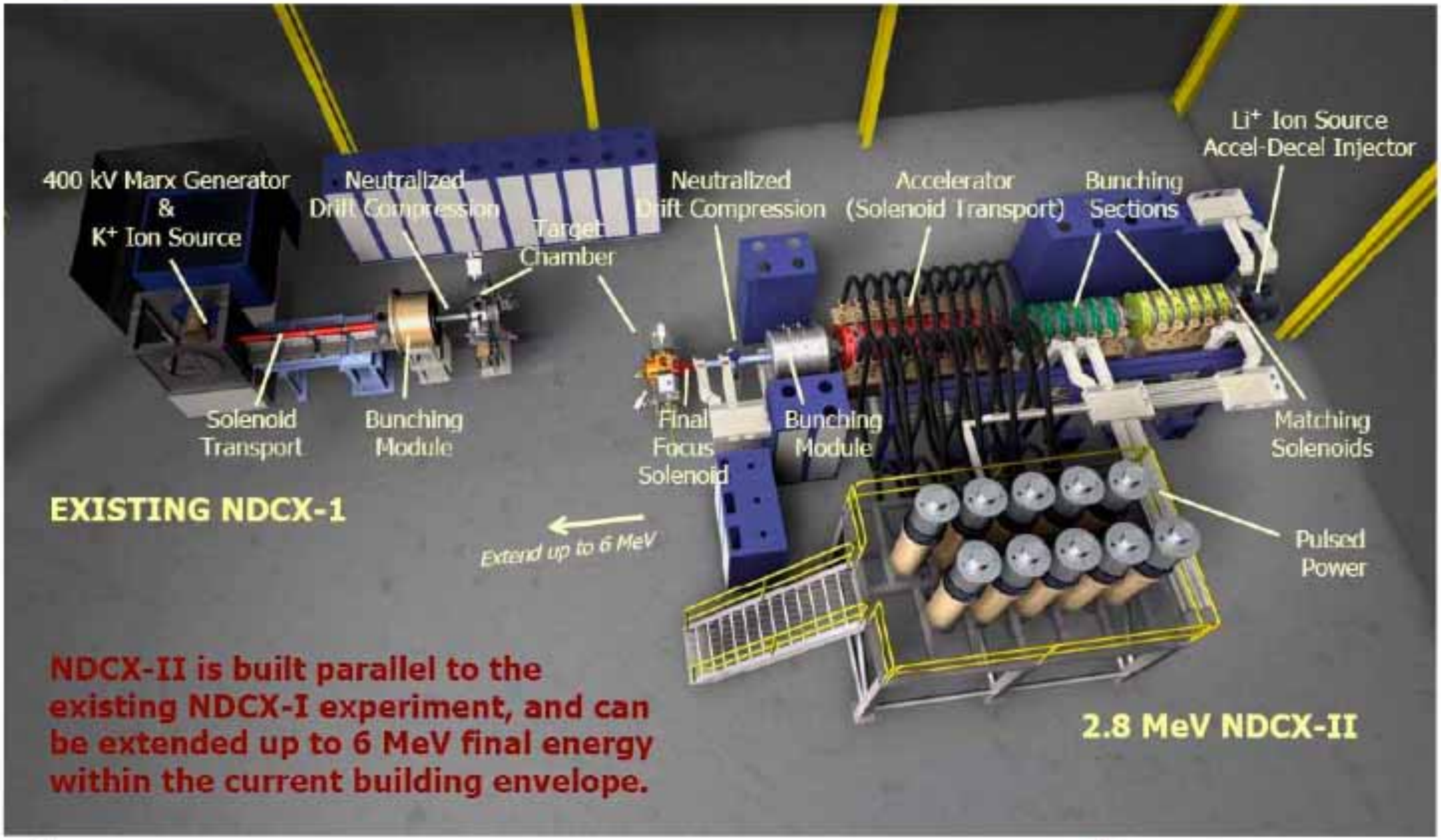


LLNL has donated 30 surplus ATA induction modules now located at LBNL- sufficient for NDCX-II



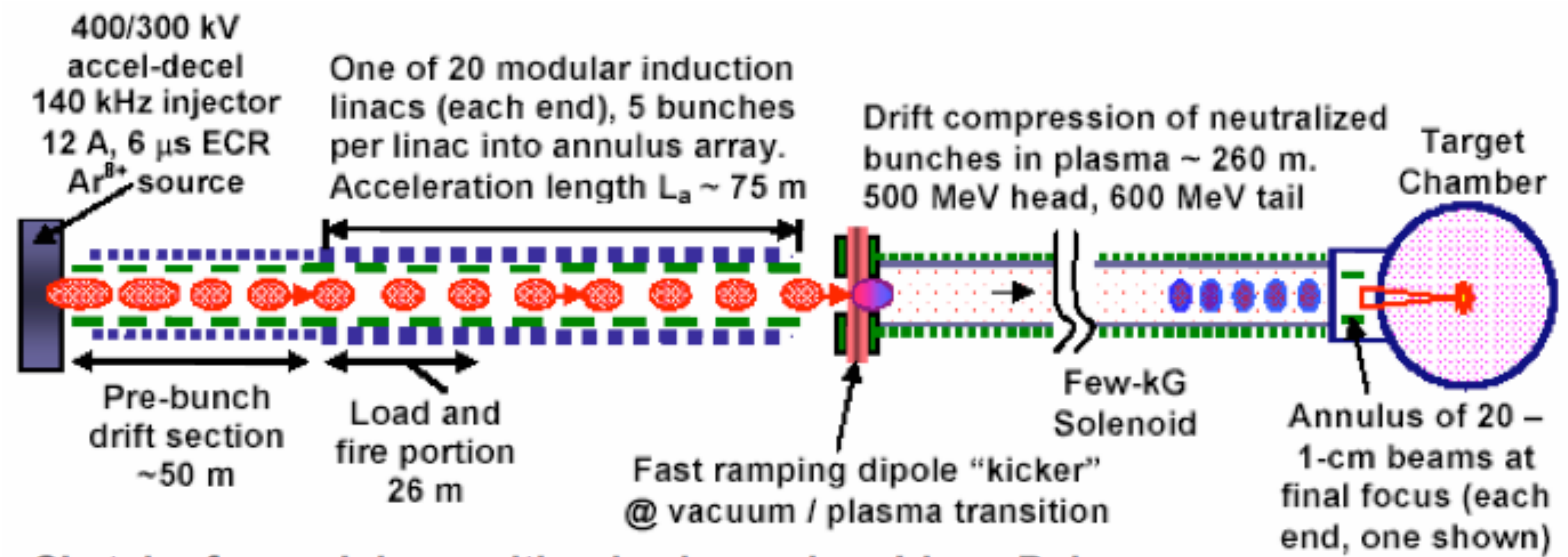
- We have shipped hardware for 30 induction cells to LBNL.
- We are building a high-field pulsed solenoid to fit into an ATA induction cell for tests.
- Hardware for two cell units has been refurbished for testing.

The FY09 request budget with $1.3 M for hardware would compete 2/3 of NDCX-II assembly using existing ATA equipment now at LBNL.



[redacted]

Work in progress: we are evaluating ways to apply what we learn from our HEDP research towards heavy ion fusion energy

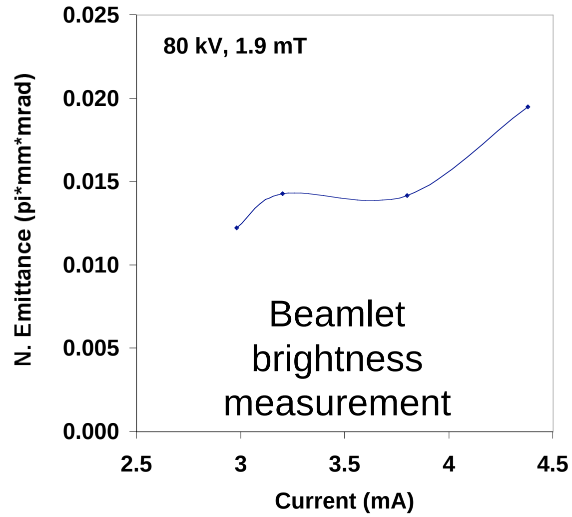


Sketch of a modular, multi-pulse heavy ion driver. Pulses overlap at the target→ 500 TW peak power in 2 ns → < 1 MJ driver? (TBD)

→Key enabling advances that will help <u>both HEDP and fusion</u>:

- **Neutralized drift compression and focusing.**
- **Time-dependent correction for improved achromatic focusing.**
- **Multi-pulse longitudinal merging and pulse shaping.**
- **Fast agile optically-driven solid state switching.**

Source-Injector test facility (STS)

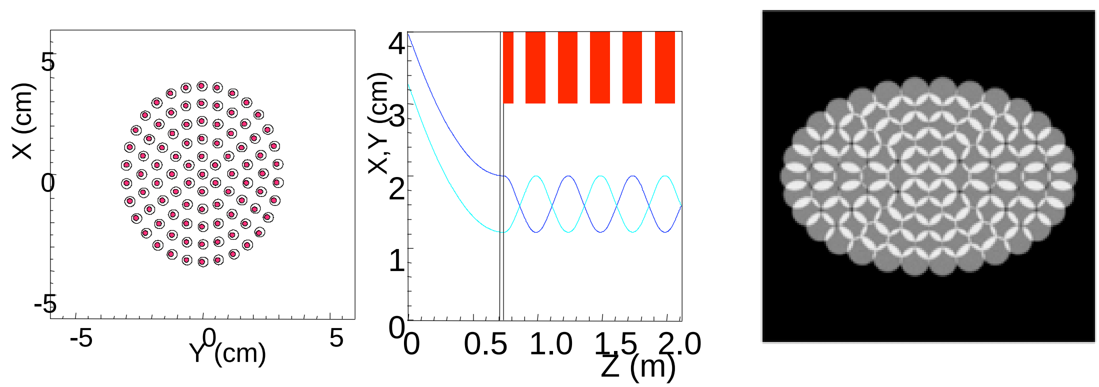


Injector Brightness:

source brightness,

aberration control with apertures,

beamlet merging effects



3-D simulation of multiple beamlets